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An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications

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About this Document

Why read this report?

Extensive LCA research has been done on food and beverage packaging, and the knowledge base continues to grow. This report sought to capture this knowledge to help focus and direct food and beverage packaging-related conversations and the design of future LCA studies on packaging systems, with the aim of improving the information transfer among executive leadership within companies, non-LCA users, LCA Practitioners, and/or commissioners. The analysis provides practical guidance to support decision making regarding environmental performance of packaging for food and beverage applications in order to address increasing expectations on the packaging industry. In addition, it provides a foundation of understanding for other packaging stakeholders (consumers, retailers, NGOs, etc.) of the challenges and opportunities related to driving common environmental sustainability goals for packaging in the food and beverage industry. This is achieved through a systematic extraction of knowledge from existing LCA studies in order to articulate the value of applying LCA to food and beverage packaging. Food and beverage products, while occasionally included in packaging analyses, is not addressed directly as the focus is on the packaging itself. The conclusions drawn in this study represent the foundation for future research on the environmental impact of packaging in this industry.

Audience and intended uses

The themes of this research are relevant to a broad range of professionals in the packaging value chain, as well as others interested in life cycle thinking and sustainability in the food and beverage industry generally. Life cycle assessment (LCA) practitioners will be able to glean new insights about applying this methodology to packaging and other applications. Packaging designers and governmental policymakers will find guidance about applying the insights of this analysis in Sections 6 and 7. Advocates or advisors of the food and beverage industry, such as non-governmental organizations, can also leverage the findings for work on other issues, like waste management. Entities wishing to conduct future knowledge mining of LCA will find a presentation of a proposed methodology for knowledge mining.

Contents

1. Executive Summary

Packaging plays a critical role in the labeling, transportation, protection, and preservation of food and beverage products. Growing concern for the environment, combined with the ubiquity and visibility of packaging, however, has led to increasing scrutiny of packaging's environmental burdens by a variety of stakeholders. Significant research has been done to quantify the environmental impacts of packaging for this industry—whether through life cycle assessment or other means—in order to reduce costs and improve performance. The aggregate knowledge resulting from this research is highly informative to decision-makers. This report summarizes the results of a project designed to consolidate outcomes of existing research on the environmental performance of packaging, namely life cycle assessment (LCA) studies, in order to demonstrate the value of applying LCA to inform decisions when evaluating food and beverage packaging.

Life cycle assessment is a quantitative evaluation of the environmental performance of a product system across its life cycle. While LCA does not represent a complete set of potential environmental, social, or economic impacts to be optimized for packaging, it provides a replicable and rigorous methodology for evaluating several key environmental metrics of priority to the sector and its customers.

To conduct the analysis, the authors systematically analyzed 69 existing LCA studies, primarily conducted in Europe and North America, representing food and beverage products and/or their packaging. Key findings were extracted from those studies and common outcomes were identified that illustrated the value of an LCA-based approach. The outcomes of this study were also evaluated as a UNEP/SETAC Life Cycle Initiative effort to pilot knowledge mining of LCAs as a generalizable methodology for other applications. The detail of this methodology and the research questions are outlined in the Technical Summary.

Key messages from this analysis include:

1. Life Cycle Assessment helps encourage a transition away from focus on single-issue environmental priorities and provide insurance that environmental burdens are not shifted from one life cycle stage to another (e.g., from manufacturing to raw material production). In other words, LCA results make it more difficult to make decisions that are out of context for the product or environmental impacts being optimized.
2. There are few, if any, generalities about what makes a package environmentally preferable in terms of materials or design attributes. LCA provides a standardized and objective framework for conducting such evaluations and comparisons. The optimal packaging design from an environmental performance standpoint will vary according to packaging system characteristics such as raw materials chosen for use, the specific product being packaged, and the corresponding supply chain.
3. A detailed cradle-to-grave LCA may not be required for every type of decision to be made about packaging design, manufacturing, and governmental policymaking.

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Qualitative consideration of the broader life cycle may be sufficient to guide many decisions, and streamlined LCA tools are available for directional analyses.

4. LCA is a highly valuable tool in driving more environmentally preferable packaging, and can be supplemented by other tools to measure other important economic, technical, or social characteristics depending on the objectives and values of the user.
5. LCA is a tool that can be used to support decision making by providing environmental data and information. Ultimately, it is the decision maker's responsibility to decide which metrics should factor into the decision and how to address any trade-offs among alternatives. Additionally, LCA quantifies environmental performance; risk assessment and social sustainability are two examples of business concerns that cannot be addressed with LCA.
6. The waste management hierarchy can be a good rule of thumb for directional evaluations and can give appropriate recommendations in specific cases (e.g., single-material analyses), but may not be appropriate for some evaluations, such as comparisons involving packaging designs manufactured from different materials (e.g., glass versus plastic).

In addition, the learnings from knowledge mining provide practical implications for conducting future food and beverage packaging LCAs, for developing governmental policy related to packaging, and for designing more environmentally preferable packaging, including the following:

- Keep in mind, when designing packaging or government policy, that the primary purpose of packaging is product protection, while optimizing packaging efficiency and effectiveness.
- Conduct life cycle assessments when appropriate. Not every question requires a detailed LCA to answer; tools to conduct high quality, but expedited, LCAs are available. In cases when an LCA is necessary, the analysis should account for all differences in packaging designs, such as product loss or more efficient cube utilization.
- Be fully informed about the trade-offs among environmental indicators as quantified by LCA and other commitments and business priorities required when making design and policy decisions.
- Design governmental policies that do not favor one material or design attribute over another, but rather aim to achieve a desired environmental outcome (e.g., reduced greenhouse gas emissions) and allow the packaging decision maker to choose the optimal material.
- Identify governmental policy objectives that link to broader environmental priorities of the government or policymaking body. The resulting policy should align with government or organization goals and address the root causes of environmental impacts of packaging systems rather than target "superficial fixes".
- Incorporate regional variations to account for differences in culture and consumer behavior, waste infrastructure, and local government objectives.

Recommendations for further research include expanding knowledge mining beyond LCA literature, expanding the analysis to include mining of actual data from LCA studies, investigating the role of LCA in addressing national and global issues as well as those of small and medium sized enterprises, evaluating the extent of differences in LCAs conducted for OECD countries versus developing economies, understanding the value of LCA-based design and LCA-driven marketing messages beyond cost reduction or product environmental performance improvement, and quantifying the benefits of food and beverage packaging and its potential to reduce food waste (particularly in developing economies).

2. Technical Summary

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To achieve the goals of this study, the authors systematically analyzed 69 existing LCA studies to extract key points and identify knowledge and learnings that illustrate the value of LCA. The methodology involved first defining research questions and developing attribute and relevance matrices to document the studies and assess study quality. Collected literature was then reviewed and characteristics of each study were captured in the attribute matrix. Key findings were then extracted by the project team, who applied expert judgment to ensure these findings were indeed supported by the various studies given analysis assumptions and results. Lastly, overall learnings were generated based on the frequency and nature of key findings. Where possible, learning strengths and weaknesses were assessed in light of the studies reviewed. The methodology applied in this study was targeted toward mining knowledge from existing LCA studies, but can be generalized to mining knowledge in other areas of interest.

Utilizing this methodology, the following learnings were extracted from existing LCA literature:

1. Why adopt a life cycle approach to food and beverage packaging?
    - By using LCA, a decision maker can avoid shifting environmental burdens to life cycle stages or components outside system boundaries.
    - LCA impact categories such as global warming potential represent holistic results that reflect a product's life cycle rather than metrics that refer to a specific attribute, such as fraction of recycled content or renewable content, that focus on one element of packaging design. Single attributes are not guaranteed to positively correlate with reduced environmental burdens, especially when cross-material comparisons are conducted.
    - The context-dependence of LCA results means outcomes often cannot be generalized and strongly depend on the packaging system characteristics. Consequently, it is not possible to identify a single best material for all packaging applications or a single best disposal pathway for a given material.
2. Why assess the full life cycle when evaluating food and beverage packaging systems?
    - Including all life cycle stages is critical because it prevents the decision maker from inadvertently shifting the environmental burdens from one stage to another that lies outside system boundaries. It also ensures that potential impacts at all life cycle stages are accounted for and that the decision maker is not omitting a life cycle stage that, if disregarded, could potentially alter packaging system preference.
3. Why evaluate multiple life cycle impact categories?
    - Including multiple environmental performance metrics is also valuable in order to avoid shifting the burdens from one impact category to another (e.g., from climate change impacts to eutrophication impacts).
4. Why include food and/or beverage in the packaging life cycle assessment?
    - In supply chains, packaging seldom exists without a product. The package is an integrated part of a supply chain system and, as such, should not be assessed without the product for which it exists.
    - When food or beverage are included within analysis boundaries, it's seen that food packaging is often—but not always—a minor contributor to the total environmental impact of a food product's life cycle, whereas beverage packaging represents anywhere from a minor to a significant contribution to a beverage product's total impact due to the wide variation in (absolute) product impact. As

such, optimizing environmental impact of packaging requires a broader assessment.

- It is important to include product loss from damage (e.g., during distribution and retail) or spillage (e.g. during filling) to ensure the burdens are not shifted from packaging to product.

5. What is the intersection of the waste management hierarchy and LCA results?
    - The waste management hierarchy (reduce, reuse, recycle, dispose) provides guidance for packaging waste reduction; however, its preference order for disposal pathways does not always align with preference as determined from LCA results. It is important then to consider multiple priorities and the broader life cycle to make informed decisions.
    - A material's optimal recycling rate, above which the environmental burdens to collect and process the marginal amount of material will exceed any marginal impact reduction from use of secondary material, will depend on collection system logistics, primary material production burden, and secondary material production burden.

In sum, the studies evaluated demonstrated the value of taking a life cycle approach to answer the questions posed by the various researchers of the analyzed studies. Additionally, illustrating the value of applying LCA to food and beverage packaging, the learnings are also drawn upon to provide practical advice for conducting future food and beverage packaging LCAs. By ensuring the LCA is properly scoped and carried out, a decision maker can reduce the probability of suboptimal packaging-related decisions. LCA is also shown to be important not only to packaging designers, but also to others involved in the packaging value chain, such as governments and others involved in policy management. Through use of LCA—and more generally, life cycle thinking—decision makers can make more informed choices and ensure those choices do indeed lead to improved environmental performance of packaging.

Results are shared in detail in Section 5 and the method applied to conduct the knowledge mining detailed in Appendix C.

3. Overview

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Packaging for food and beverage products is under increasing scrutiny by consumers, retailers, regulators, and food and beverage manufacturers, and as such is particularly valuable to analyze in detail for environmental performance using the application of life cycle thinking, in the context of the function of the packaging. Long-term experience with LCA in this sector, combined with the importance of the sector, led the UNEP/SETAC Life Cycle Initiative to identify food and beverage packaging as the priority for application of this concept when the Initiative began the effort of establishing a knowledge mining methodology for LCAs. The objective, then, of this analysis was to conduct a detailed evaluation of existing life cycle assessment studies for food and beverage packaging to extract insights representing the body of knowledge about environmental impacts, to inform decision-makers related to packaging about key considerations in taking a life cycle approach that would ultimately reduce environmental impacts.

Motivated by increasing demands on packaging to be more environmentally sound, extensive LCA and other environmental performance research have been—and continue to be—conducted on food and beverage packaging. As such, the UNEP/SETAC Life Cycle Initiative, as part of its mandate to educate and promote life cycle thinking, posited "Is there a way to learn from those studies to help focus and direct food and beverage packaging-related conversations and the design of future LCA studies on packaging systems, with the aim of improving the information transfer among executive leadership within companies, non- LCA users, LCA practitioners, and/or commissioners?" The question brought forth a proposed effort within the Initiative to develop a methodology that would consolidate knowledge from existing LCA studies that could specifically be applied to articulate the value of applying LCA to food and beverage packaging, and to extrapolate from this analysis the implications for key stakeholders of the packaging and food & beverage industries—specifically packaging designers, LCA practitioners, and governmental policy and other decision makers.

The foremost role of packaging is to protect and contain the product during distribution and storage. When designed intelligently, it can ensure product safety—particularly important for food

and beverages—and minimize losses. In the food and beverage industry, packaging also serves to preserve the product and prevent spoilage, provide information, provide convenience and portion control, and market to the consumer[1]. Given this diversity of important functions, combined with the complexity of the value chain and the increasing expectations of consumers, retailers, and other stakeholders, optimizing the environmental performance of food and beverage packaging from an environmental perspective, while acknowledging these various expectations, presents challenges and opportunities.

The methodology developed to answer this question (see appendix for more details) provides a process for consolidating outcomes of LCAs through knowledge mining[2], in which publications are systematically reviewed for relevance and quality, and their key findings are extracted and organized into 'learnings', which are used to support understanding and decision making related to products—in this case, food and beverage packaging.

1 K. Marsh and B. Bugusu, "Food Packaging—Roles, Materials, and Environmental Issues," Institute of Food Technologists, 72:3, p. R39, 2007.
2 Knowledge mining is a general concept in which a body of information is meta-analyzed to develop insights that can either reinforce or supplement currently available knowledge or literature. It differs from data mining in that it seeks to extract qualitative guidance and observations based on the information reviewed, whereas the latter aims to generate statistics from large sets of data. This study sought to define a knowledge mining methodology specifically for reviewing life cycle assessment information.

3.1 Scope

The themes of this research are relevant to a broad range of professionals—not only those in the packaging value chain, but also others interested in this type of thinking or who are not experts at LCA and the food and beverage industry generally. Advocates or advisors of the food and beverage industry, such as non-governmental organizations, can also leverage the findings for work on other issues, like waste reduction or packaging recovery. Given that this report focuses on environmental sustainability in food and beverage packaging, LCA practitioners will be able to glean new insights about applying this methodology to other applications.

The LCAs reviewed for this analysis were conducted at the package or product level; consequently, outcomes of the knowledge mining do not consider macro issues such as resource conservation or food availability at a national or global level. In addition, this study strives for a material-neutral approach as LCA is a framework to evaluate environmental performance whose results can inform decision-making—not a formal decision-making tool. Consequently, this study does ***not*** include a comprehensive list of material options for packaging, nor does it assess material preference or state which material or design concept is best or worst. It is not meant to be a consumer guide for purchasing products with minimal packaging. While this study evaluates the usefulness of life cycle assessment in packaging design, it is not inclusive enough of all performance or cost aspects of packaging to be a general packaging design guide. The emphasis on LCA also means any report findings are limited to environmental sustainability as the LCA methodology is primarily designed for quantifying environmental impacts. Other applications of life cycle thinking, such as life cycle costing or social life cycle assessment, that address economic, social, or other aspects of sustainability from a life cycle perspective are ***not*** covered in this report.

4. Life Cycle Approaches

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4.1 What is Life Cycle Thinking?

Before the research results are presented, it is important to articulate the foundational concepts being evaluated in this knowledge mining effort. The concept of life cycle thinking is about evaluating the economic, environmental, and social impacts of a product beyond the manufacture or use of a product (or the delivery or use of a service) from "cradle-to-grave", starting with the extraction of natural resources to final disposal of the product, including any material recycling, energy recovery, or reuse that may occur prior to ultimate disposition. Adopting life cycle thinking can provide decision support for businesses striving to reduce the impact of providing products and services, because it can be used to evaluate whether actions translate to actual improved performance without inadvertently increasing or transferring the burdens elsewhere. Several applications of life cycle thinking exist, including life cycle assessment (environmental), life cycle costing (economic), and social life cycle assessment (social). By considering the impacts associated with a system's full life cycle, decision makers can avoid shifting burdens from one life cycle stage to another—thus ideally minimizing the product or process' overall impact. Previous work published by the UNEP/SETAC Life Cycle Initiative illustrates potential benefits of life cycle approaches and provides guidance in implementing the framework[3,4,5]

4.2 What is Life Cycle Assessment?

In order to ensure understanding of the nature of the studies mined for knowledge, it is valuable to articulate the basic approach to conducting an LCA. Life cycle assessment (LCA) is a quantitative application of life cycle thinking for evaluating the life cycle environmental performance of a product or service. It represents a well-developed framework that can be used to guide environmental decisions in a number of industries. As such, LCA has been extensively researched—both the methodology and applications of the framework. LCA itself, however, is not a decision making tool but rather, a means to better inform decisions.

Specifically, LCA enables decision makers to evaluate the environmental performance of a product system in terms of all of the steps related to creating that product, from growing agricultural product, transportation, processing and manufacturing, through retail and distribution, and thus avoid shifting the burden from one of these steps to another. LCA also enables quantification of multiple environmental impacts that address various issues of concern (e.g., climate change) so that the decision maker can understand what trade-offs may need to be made. Lastly, LCA is flexible and can be applied focused on the key questions a decision maker should be considering when evaluating packaging options.

According to ISO standards 14040[6] and 14044[7] for LCA, the methodology refers to the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system, scaled to a functional unit, throughout its life cycle. To understand the nature of the studies used to develop recommendations in this paper, it is useful to understand what conducting an LCA entails.

There are four phases defined by ISO a practitioner follows when conducting an LCA:

- Goal and scope definition
- Life cycle inventory analysis
- Life cycle impact assessment
- Interpretation

3 J. Fava and J. Hall, *Why Take a Life Cycle Approach?*, UNEP/SETAC Life Cycle Initiative, 2004.
4 *Life Cycle Management: How business uses it to decrease footprint, create opportunities and make value chains more sustainable*, UNEP/SETAC Life Cycle Initiative, 2009.
5 *Towards a Life Cycle Sustainability Assessment: Making informed choices on products*, UNEP/SETAC Life Cycle Initiative, 2011.

6 ISO, Environmental management — Life cycle assessment — Principles and framework, 14040:2006.
7 ISO, Environmental management — Life cycle assessment — Requirements and guidelines, 14044:2006.

During the goal and scope definition, a practitioner outlines his reasons for conducting an LCA and specifies the system under study. This specification includes defining the functional unit, the reference unit that represents the level of performance of the product system (e.g., an LCA evaluating alternative packaging designs for a gallon of milk might define the functional unit as "delivery of 50 gallons of milk to a consumer household"), and setting system boundaries, which states what steps and activities are included in the analysis. For example, if the packaged product under study does not require refrigeration (e.g., cereal), consumer use may be excluded from the analysis.

Once study scope has been defined, the life cycle inventory is compiled. This inventory represents a list of resources consumed (e.g., crude oil, bauxite ore) and emissions generated (e.g., carbon dioxide released into the atmosphere, nitrates released to groundwater) throughout the product system's life cycle.

The inventory is used in the next phase, life cycle impact assessment, for calculating impact category indicator results. During this phase, emissions and resources are "characterized" based on their potential to contribute to some environmental concern such as resource depletion or climate change. Characterization is often done using characterization methodologies such as TRACI 2.0[8] and ReCiPe[9]. Impact category indicators include, but are not limited to, abiotic resource depletion, global warming, and eutrophication, all of which represent potential impacts on the environment from resource consumption and emissions[10]. Different indicators are considered depending on their importance and relevance to the system under study. It is up to the practitioner to justify impact indicator exclusion (or inclusion) in the analysis based on the values and goals of the organization conducting the LCA.

In the final phase, interpretation, LCA impact category results are evaluated in light of system boundaries and other scoping assumptions, data collected, and assumptions made to generate the life cycle inventory. Additional, more detailed, information on LCA can be found in a number of references[11,12,13].

As noted above, LCA is a framework for quantifying the environmental performance of a product. Results represent the potential environmental impact of the product under study for various environmental issues of concern, such as climate change or air quality. Interpretation is necessary in order to understand limitations of which conclusions are possible and which are not. LCA is often used to identify environmental hot spots, understand trade-offs between alternative product or system designs, facilitate supplier and customer communications, or to support marketing claims.

It should be mentioned that characterization methodologies for some impact categories such as land use (occupation and transformation), water scarcity, and biodiversity are still evolving. Non-environmental concerns like the aesthetic impact of packaging litter fall outside the scope of LCA or have not yet been addressed within the LCA framework. Assessments involving economic or social aspects rely on other life cycle thinking applications like life cycle costing (LCC) or life cycle working environment (LCWE).

8 J. Bare, "TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0," Clean Technologies and Environmental Policy, 13:5, p. 687, 2011.

9 M. Goedkoop et al., "ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level", 2006. Available from: www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf (accessed 2013-Jan-14).

10 Due to its relative approach, which is structured around a functional unit, and other reasons, LCA cannot predict absolute or precise environmental impacts or the exceeding of thresholds, safety margins or risks (see ISO 14040:2006, section 4.3).

11 H. Baumann and A.-M. Tillman, The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application, Lund, Sweden: Studentlitteratur, 2004.

12 A. Remmen, A.A. Jensen, and J. Frydendal, Life Cycle Management: A business guide to sustainability, Nairobi: United Nations, 2007.

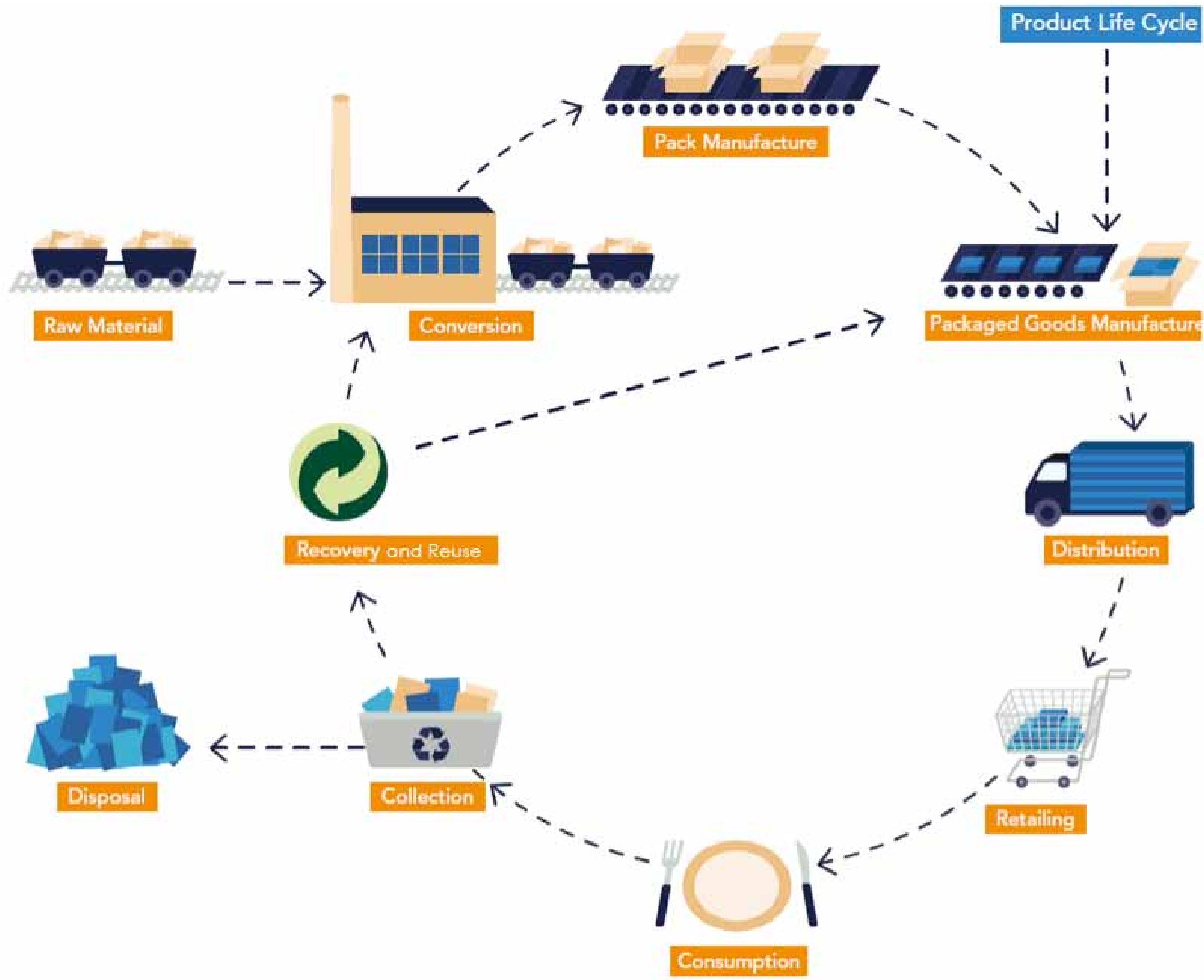
13 H.A. Udo de Haes and M. van Rooijen, Life Cycle Approaches: The road from analysis to practice, UNEP/SETAC Life Cycle Initiative, 2005.

4.3 Packaging and Life Cycle Assessment

Packaging is an often-studied LCA topic, either as part of a larger product system or by itself to enable a manufacturer to understand design trade-offs or communicate environmental performance; this foundation of research provides the groundwork of the analysis presented in the next section. Improved packaging designs can potentially reduce the environmental impact of packaging, and LCA provides a means to quantify that performance on certain metrics. Environmental impact is of particular concern, as packaging is often perceived as waste by consumers and retailers. Many brands have begun to differentiate themselves by adopting packaging materials and systems that are perceived to be "environmentally-responsible".

The life of packaging is outlined in Figure 4-1 to illustrate what an LCA seeks to evaluate about packaging. In brief, packaging raw materials,

Figure 4-1: Food packaging life cycle example



Source: Adapted from:
EUROPEN and ECR Europe, Packaging in the Sustainability Agenda: A Guide for Corporate Decision Makers, 2009.

such as plastic granulate, are produced from non-renewable, renewable, or recycled resources. These materials are subsequently converted to bottles, boxes, and other packages that are filled by a food or beverage processor. The packaged product is then distributed to retailers, who reuse the shipment packaging (i.e. secondary and tertiary packaging such as pallets or corrugate boxes) or send it out for recovery or disposal. In the case of reusable packaging, a cleaning step may be necessary to prepare the package for its subsequent use; otherwise, the use stage is typically not associated with packaging. Consumers purchase the food or beverage contained within the primary packaging; at home, they prepare and consume the food or beverage and dispose this packaging.

Depending on the objectives of a particular analysis, LCAs of packaging can be conducted on the packaging itself—for example, to evaluate alternative packaging designs for a particular product—or include packaging as a part of a larger product system to understand the impacts of a product overall. Whether the packaging is for food, beverages, personal care products, or building materials, the challenges are often the same: how to minimize its environmental impact without compromising the product it is meant to support.

Evaluating this balance should be informed by sound scientific thinking. LCA provides a framework to guide the development of environmentally preferable packaging in this industry and ensure that companies consider not just the impacts of raw materials or manufacturing, but the entire packaging life cycle and how packaging can influence product losses. Applying life cycle-based practices can ensure that environmental burdens are not simply transferred from one stage or component of the life cycle to another and offers a method for considering the role packaging plays in protecting and marketing the product. The benefits of LCA and its critical review process can, therefore, set a foundation to optimize the environmental performance of packaging.

This project served to demonstrate these very points from the mining of knowledge from existing LCAs.

5. Knowledge Mining Results

5

This section articulates the results of the knowledge mining exercise of food and beverage packaging LCA studies. Research questions were defined, collected literature reviewed, and key findings extracted by the project team conducting the knowledge mining, who applied expert judgment to ensure these findings were indeed supported by the various studies given the analysis assumptions and results (see appendix for details). Results are presented in the form of learnings that aim to illustrate the value of applying life cycle assessment when evaluating the environmental performance of food and beverage packaging. Only learnings are presented in this chapter. Applications of these findings and implications of results on decision-making for different stakeholders are discussed in Sections 6 through 8.

Findings are organized by research questions. Since this study aims to generally articulate the value of applying LCA to food and beverage packaging, the questions are centered on this goal. Additionally, LCA results are examined in relation to the waste management hierarchy in order to better understand when it may be beneficial to further inform the decision with an LCA.

5.1 Why adopt a life cycle approach to food and beverage packaging?

An overarching goal of this analysis is simply to demonstrate in general why one should adopt a life cycle perspective when evaluating the environmental impact of food and beverage packaging. In addition, several sub-questions related to the specifics of a life cycle approach are also investigated in detail:

- Inclusion of multiple attributes
- Inclusion of all life cycle stages
- Inclusion of the product in the analysis

While study goals and application of results may differ, the same LCA methodology applies regardless of whether the packaging is produced for developing or developed economies

This section addresses the value of adopting a life cycle approach—in particular for comparisons of packaging designs that use different materials. Life cycle assessment enables a practitioner to rigorously quantify resource consumption and emissions associated with a product system, and to translate those flows to potential environmental impacts. This rigorous quantification can, in turn, be incorporated into the decision-making process so that the decision maker is not only relying on an internationally standardized and accepted methodology, but also employing science-based analysis rather than intuition or anecdotal information to assess packaging environmental performance.

Another value is that the LCA methodology is applicable regardless of geographic scope of the analysis or, for that matter, the practitioner's or decision maker's locations. While outcomes may differ, the approach is the same when applied to food and beverage packaging in both emerging and developed economies (see Box 1 on LCA and developing economies). A valid analysis, however, will always require that the practitioner properly evaluate the environmental performance, as a lack of rigor and lack of life cycle-based metrics can lead to suboptimal decisions. Numerous studies identified during the knowledge mining exercise support this conclusion and suggest that when a life cycle perspective is not adopted, a decision maker may inadvertently increase environmental burdens.

Existing LCAs show that a life cycle perspective is particularly necessary when evaluating alternative packaging designs manufactured from different materials. The "less is better" solution holds true: a comparison of two functionally equivalent packaging designs of the same material and using the same manufacturing process is almost guaranteed to show that the lower-weight design will be associated with lower environmental burdens since it uses less material, consumes fewer resources to transport and shape the material, and leads to less waste (assuming, of course, that the lower-weight design does not compromise product protection and increase product loss). When ***cross-material comparisons***[14] are conducted, however, the preferred material is not as obvious as each material is associated with its own physical properties that influence the package design and environmental burdens.

Packaging design properties like renewable content are easier to measure and design for than environmental performance as measured by LCA; however, improvements in these properties are not guaranteed to translate to improvements in environmental performance

Knowledge mining outcomes indicate that the use of package design properties, such as the fraction of recycled content or renewable material content, to represent environmental performance is often not appropriate for cross-material comparisons. Unlike life cycle impact indicators, these properties do not measure the environmental burdens associated with all the stages of the life cycle; consequently, improvements in these properties may, but are not guaranteed to, lead to improvements in environmental performance. This is supported by the Global Packaging Project's document on packaging indicators, which recommends that both packaging design properties and life cycle impact categories be used to evaluate packaging sustainability performance [1]. Examples of knowledge mining outcomes that illustrate the counterpoint—specifically, that improving packaging design properties does not always correlate with improving environmental performance—are detailed below for cross-material comparisons.

- Choosing a packaging material solely based on recycling rate may lead a decision maker to overlook alternative options that are less readily recycled but may potentially lead to lower cradle-to-grave environmental impact for a particular metric. Humbert [2], for example, compares two alternative packaging designs for baby food. According to Humbert's results, the design with the higher recycling rate is generally associated with the higher environmental burden for the various impact categories owing to that design's higher raw material burden. Likewise, a study by TetraPak [3] illustrates a similar point: that one-liter juice bottles manufactured from certain materials can out-perform functionally equivalent packages manufactured from alternative materials despite the lower recycling rate of the former. Alternatively, the opposite can be true and the packaging design with the higher recycling rate preferred [4]. Additional examples can be found by comparing alternatives in [3–9].
- Like a material's recycling rate, solid waste minimization is a metric that does not fully encompass life cycle environmental burdens. Conducting cross-material comparisons that emphasize minimizing solid waste can potentially lead to packaging designs that

14 Cross-material comparisons of packaging designs represent analyses in which alternative designs manufactured from different materials are evaluated and results compared (e.g., glass versus plastic).

are associated with minimal waste, but when evaluated using LCA lead to increased energy demand from raw material production or other life cycle stages (e.g., see [8,10–13]).

- Similar precautions apply when the design goal is to replace disposable packaging with reusable packaging: doing so can lower environmental burdens for certain product systems (e.g., [14–17]) but depending on the system evaluated can also result in the opposite conclusion depending on impact categories evaluated or materials under consideration (e.g., [18–20]). Ultimately, it will depend on the relative mass of the disposable and reusable package alternatives, the materials from which each is manufactured, resource intensity and frequency of cleaning the reusable package, and other factors.
- Renewable content is another metric of interest in packaging, in part driven by growing concerns over the limits of non-renewable resources. The potential compostability of packaging manufactured from agricultural resources is also generating attention since composting offers a means to reduce solid waste. From an LCA standpoint, however, packaging produced from renewable feedstock is not necessarily associated with lower environmental burdens than packaging derived from non-renewable feedstock, because the balance of energy required to grow, harvest, and process the renewable feedstock can sometimes outweigh that of a petroleum-based. This is illustrated by literature in which both renewable and non-renewable packaging designs are compared (e.g., [3,4,8,18,19,21–24]).

To reiterate, decisions based on packaging design properties alone cannot guarantee that a package associated with a higher property value will have better environmental performance (as determined by LCA) than one associated with a lower property value. This incomplete picture may lead the decision maker to suboptimal decisions that may inadvertently increase impact—particularly for comparative analyses that evaluate alternative packaging designs based on different materials. This is not to say that such packaging design property metrics are not valuable. The metrics are often easier to measure and design for than indicators used in LCA and can potentially serve as proxies for environmental performance. The practitioner, however, will need to show that improvements in these metrics do indeed translate to reduction in environmental burdens over time.

It should also be noted that should LCA be used to evaluate packaging environmental performance, the results will ultimately depend on the packaging design specifics, study context, and environmental impact category indicators considered. (The choice of category indicators is of particular importance as, in order for the analysis to comply with ISO standards, category indicators must be relevant to the product system under study and the ones selected (or excluded) justified by the practitioner. Section 5.1.2 addresses why considering multiple impact categories is important.) Consequently, it is not possible to generalize LCA results and state unequivocally that one material is always "better" than another or that one packaging design is always "better" than another.

It is not possible to generalize results from comparative packaging LCAs as the preferred design will depend on application specifics

Equally important is for the practitioner and decision maker to recognize the pros and cons of each material in a cross-material comparison and to make informed trade-offs. While some materials may enable a lighter weight package, there may be a trade-off between energy consumption or greenhouse gas emissions when the package's environmental performance is

Box 1: LCA and developing economies

The knowledge mining conducted in this analysis drew mostly from LCA studies that evaluated packaging in Europe and North America, due to limited availability of studies in English that evaluated packaging in other regions. Basic results, however, are expected to be applicable anywhere LCA is conducted. Whether the analysis is geographically scoped to an emerging economy or a developed nation, the same ISO standards and methodology apply. Practitioners follow the same process of defining goal and scope, compiling a life cycle inventory, calculating impact assessment results, and interpreting the analysis. Examples of this similarity are illustrated by three LCAs conducted for packaging in Brazil, China, and Mexico[a-c].

Elements of the analysis may differ, but the value and application of the approach remain the same. Study goals, for example, may change according to whether the LCA is conducted from a developing economy's perspective versus from a developed economy's perspective owing to different concerns and priorities of developing economies. In developing economies for instance, the majority of food losses take place along supply chain before food reaches the consumer—thus necessitating different solutions that would not apply in a developed economy, where most waste occurs by the consumer[d]. These losses are often due to lack of distribution and storage infrastructure, as well as lack of processing facilities and inadequate market systems[d]. So, packaging can play a role in a developing nation's economy, not only by reducing food loss but also by enabling the nation to package food near where it's grown and thus enhance product value on the world market[e]. Optimizing efficiency and effectiveness of packaging would still need to be quantified by evaluating the full product system life cycle, thus making a life cycle approach applicable even if the decisions resulting from the LCA are different. This point was not able to be validated through available LCAs, but may be a key potential future research question for guiding decision making about packaging design. Regardless, the method to quantify the environmental impact of that packaging will remain the same.

In sum, while problems are different, LCA principles and the value of its outcomes are still the same. Findings from the knowledge mining exercise can still be relevant—for example, the fact that regional infrastructure will influence optimization of environmental burden at end-of-life and that preference for a particular end-of-life pathway will ultimately determine performance, cost, reliability, and other attributes (see Section 5.2). There also remains value in adopting a life cycle perspective, considering multiple impact indicators, and including all life cycle stages, from cradle to grave. Guidance provided in this document is still relevant as it will enable a deeper understanding and more informed decisions for the environmental sustainability of food and beverage packaging.

a. A.L. Mourad, E.E.C. Garcia, G.B. Vilela, and F. Zuben, "Environmental effects from a recycling rate increase of cardboard of aseptic packaging system for milk using life cycle approach," *Int J LCA*, vol. 13, Jun. 2007, pp. 140–146.

b. H.-T. Wang et al. *Carbon Footprint of Packaging Materials from Tetra Pak Kunshan*, Sichuan University, 2010.

c. O. Romero-Hernández et al. "Environmental implications and market analysis of soft drink packaging systems in Mexico. A waste management approach," *Int J LCA*, vol. 14, Dec. 2008, pp. 107–113.

d. W. Moomaw et al. *The Critical Role of Global Food Consumption Patterns in Achieving Sustainable Food Systems and Food for All, A UNEP Discussion Paper*, UNEP, Division of Technology, Industry and Economics, Paris, France, 2012

e. J. Gustavsson et al. *Global food losses and food waste*, Rome, Italy: Food and Agriculture Organization of the UN, 2011.

f. N.M. Manalili, M.A. Dorado, and R. van Otterdijk, *Appropriate food packaging solutions for developing countries*, Rome, Italy: Food and Agriculture Organization of the United Nations, 2011.

compared to that of a package manufactured from a different material (e.g. the 34.5-oz coffee packaging systems in an American Chemistry Council's report [5]). Lightweighting packaging is not always a "better" solution if it compromises product protection (see Section 5.1.3 for a more complete discussion).

Applying life cycle thinking ensures packaging designs are assessed in the context of how they are used in a product system. The life cycle approach makes it harder to pull decisions out of context and potentially arrive at a suboptimal decision. Without the motivation to consider the full life cycle from cradle-to-grave, decision makers may be tempted to simplify the assessment by focusing on packaging materials only and comparing these materials on a mass-basis without accounting for the fact that differing amounts of each material are often required to deliver the same amount of product to a consumer (i.e., the functional unit). This is illustrated in a presentation by Denkstatt GmbH [12], which compares the global warming potential of one kilogram of various materials to the global warming potential of the same materials required to pack a specific quantity of beverage. Consideration of the full life cycle based on a common functional comparison therefore helps to better inform decision making and thus reduce system environmental impact so the burdens are not shifted from one part of the life cycle to another.

5.1.1 Why assess the full life cycle when evaluating food and beverage packaging systems?

It is important not only to adopt a life cycle approach when evaluating the environmental performance of food and beverage packaging, but also to consider the cradle-to-grave life cycle, especially when comparing alternative packaging designs based on different materials. Life cycle stages in LCA represent the different elements of the product's life cycle and are typically divided into raw materials production, manufacturing, distribution, use, and end-of-life (see Figure 4-1). Knowledge mining results indicate that regardless of how the stages are broken down, rarely is a single packaging design associated with the same level of impact in all life cycle stages (e.g., [3–6]). More often in a cross-material comparison, one packaging design will have the lowest burden in one stage and the highest burden in another making it impossible to generalize results from a single stage to the entire life cycle. Accounting of the full cradle-to-grave life cycle thus prevents a decision maker from unknowingly shifting the burdens from one stage to another stage outside the system boundaries. For example, focusing on material source only could produce a different outcome than evaluating the source plus processing requirements. This is particularly important with regard to the inclusion of the stages from gate of the packaging factory to the shelf of the retailers. Additionally, it ensures the LCA practitioner accounts for all potential life cycle impacts, given specific category indicators, in the analysis and that he or she is not omitting a life cycle stage that, if disregarded, could potentially alter packaging system preference (e.g., [7,8,25–31]).

Results from the knowledge mining exercise also demonstrate that when conducting a life cycle assessment on food and beverage packaging, it is important to consider the full cradle-to-grave impact of the packaging system in order to ensure the analysis accounts for potential system impacts. Evaluating the full system allows the decision maker to identify the dominant life cycle stage in each impact category considered. This knowledge can then be used to develop strategies to reduce environmental burdens more efficiently by targeting dominant stages. Additionally, omitting one or more life cycle stages can potentially lead to the selection of a package design that appears to have the lowest impact based on the abbreviated analysis, but is associated with the highest burden when the full cradle-to-grave LCA is evaluated. While an experienced LCA practitioner can reasonably estimate which stages will be associated with the lowest impact and therefore are least likely to influence the outcome, it is often better to assess the full package or product life cycle to confirm intuition and ensure defensible LCA results. The importance of following the accepted ISO 14040/44 standards on LCA is paramount to assure transparency and consistency in all aspects of data collection and analyses.

Transportation (including distribution), for example, is often a minor contributor to cradle-to-grave life cycle impact (e.g., [2,3,25,27,30]), especially when resource-intensive packaging materials and/or packaged products are included within system boundaries. There are instances, however, when transportation is important, such as when refrigeration is required during packaged product distribution (e.g., [32–35]). Additionally, transportation can, on occasion, dominate certain impact categories even if refrigeration is not necessary—thus preventing one from generalizing the relative contribution of transportation to a system's life cycle impact [23,26,28,36,37].

As a second example, a comparison of disposable and reusable packaging alternatives would not be appropriate if the act of cleaning the reusable package (as necessary), or its potential number of uses, were not included. Cleaning frequency or reusable package life span both influence the scope and therefore the outcomes of the analysis.

Whether or not transportation—or any other life cycle stage—dominates, however, will ultimately depend on the product system, including the exact material or product being analyzed, system boundaries, supply chain configuration, etc. as well as the impact category under consideration. It is therefore critical to consider all life cycle stages in the analysis, especially when multiple impact categories are being evaluated, since the practitioner may not be able to accurately predict which life cycle stages are associated with negligible impact and potentially misinform the decision. Inappropriate assumptions and omissions can mislead study conclusions and potentially alter packaging system preference.

5.1.2 Why evaluate multiple life cycle impact categories?

In addition to evaluating the full cradle-to-grave performance, it is also essential that a life cycle assessment evaluate multiple environmental performance indicators to avoid replacing one environmental problem with another—or at least do so with full awareness of the consequences. Assessing multiple indicators is vital, not only for compliance with ISO standards, but also because excluding impact categories can lead the decision-maker to overlook potentially important impacts or inadvertently shift the burdens to another environmental problem. Additionally, these indicators should be calculated for the entire package life cycle and not limited to a single life cycle stage or a single package design property (c.f. Section 5.1). Different life cycle stages drive different indicators; thus, as mining results indicate, a focus on a single indicator may ignore other types of potential damage to the environment. (e.g., compare life cycle stages in [33,34,38]). Transportation, for example, can—but often does not—dominate certain impact categories, including acidification potential, global warming potential, and photochemical ozone creation (smog) potential [23,26,28,36,37]. Similarly, alternative packaging designs based on different materials dominate different impact categories (e.g., [2,3,18,20,26,27,39]).

Evaluating multiple metrics is also necessary for ISO compliance given that these LCA standards do not allow for the de-selection of relevant metrics in comparative assertions intended for

> LCAs shall consider all relevant environmental impact categories in order to avoid inadvertently shifting burdens from one environmental problem to another

public disclosure. The practitioner is responsible for identifying relevant indicators and justifying his choices to include or exclude indicators. It is equally important, however, that decision makers, as representatives of stakeholder interests, take LCA results into account as it is ultimately up to them and affected stakeholders to make value choices that identify which indicators are most important for the decision and thus should form the basis of their decisions. If two or more indicators are chosen, decision makers will likely have to consider trade-offs since a packaging design is rarely associated with the lowest impact in all impact categories.

5.1.3 Why include food and/or beverage in the packaging life cycle assessment?

So far, learnings gathered from knowledge mining have primarily focused on the packaging life cycle and associated environmental impacts. LCA, however, is an adaptable and flexible methodology. Analyses need not be limited to just the packaging and can be scoped to include the packaged product—specifically the food or beverage—or product losses within system boundaries. Whether or not the product and product losses are considered will depend on LCA goals and the practitioner's reasons for carrying out the study. Only if the alternative designs are associated with equal product losses throughout the supply chain may the product and/or losses be unnecessary for inclusion. In such cases the reasons for excluding the product should be clearly stated; regardless, including the product may nonetheless be useful in that the results will show the packaging in context of how it's used: that is, to transport, protect, and preserve food and beverage.

Including product losses within system boundaries will be important if loss rates are expected to differ among alternative packaging designs—particularly when the packaging's environmental impact is anticipated to be small compared to the packaged product's impact (and therefore small compared to the impact of packaged product losses). Under these conditions, product losses may be the deciding factor in reducing impact rather than the packaging material or design. If product losses are not considered, it is important to justify their exclusion.

> If the packaging design influences product loss rates from filling, distribution, or retail, losses should be included in analysis scope as they may ultimately determine the lowest-impact design

Knowledge mining results can provide some guidance whether a package's environmental impact is expected to be small relative to that of the product or product losses. These results indicate that evaluation of the product and packaging in an individual life cycle assessment shows the package is often—but not always—a minor contributor to the environmental impact of a food product's life cycle[15]. Typically, a food product's impact is driven by agriculture and food processing, along with distribution if a refrigerated supply chain is required (e.g., [30,33,36,41–44]). Depending on the type of food, home storage and preparation may be significant factors as well [34,44]. These factors make the relevant impact from packaging smaller.

There are situations, however, in which the packaging represents a significant contribution to the food product's total life cycle impact: this is most often the case when the upstream steps to prepare a food product for sale are relatively simple or low burden [28]. Ultimately, the relative contribution of the package to a food product's

15 This is consistent with findings in the International Resource Panel Report [40] that food is one of the key contributors, along with housing, mobility, and electricity, to the environmental impacts of consumption.

environmental burdens will depend on the evaluated system (e.g., type of food or beverage, in terms of complexity and burden intensity of the supply chain from energy, chemical usage, material usage; portion size compared to packaging size; etc.), and calculated metrics.

The dependence of a package's relative contribution to environmental burdens on the evaluated system is more evident for beverage packaging. Unlike food packaging, which typically represents a minor fraction of a food product's total environmental impact, beverage packaging accounts for anywhere from a minor to a significant contribution to a beverage product's total environmental impact (e.g., [14,25,29,45–47]). This wide range is due not only to different packaging materials, but also to the wide variation in (absolute) product impact. Bottled water, for instance, requires minimal processing to prepare and package, and thus has small impact compared to its packaging [38]. By contrast, milk and wine require more energy and other resources to produce and thus are likely to be associated with higher impact than their packaging [16,28,48].

Ultimately, the purpose of including product losses is to ensure the burdens are not shifted from packaging to product. This is illustrated in Figure 5-1 (p. 24). Reducing packaging mass can reduce environmental impact—to an extent. If package mass is reduced to the point at which it can no longer protect the product from damage or preserve it on the shelf, any environmental benefit from package mass reduction is offset by additional burdens from product losses. Since the goal of conducting an LCA is often to identify opportunities to reduce total environmental burden, it is thus important to include the product especially when the packaging design can affect product loss rates.

This is particularly relevant if packaging is a small fraction of total impact, especially relative to the impact of a food product. In such cases, the impact attributed to food loss associated with

Beverage packaging can be anywhere from a minor to a significant contribution to a beverage product's total environmental impact depending on packaging material and beverage type

packaging design (e.g., from filling losses or reduction in shelf life) has the potential to exceed packaging impact alone. Indeed, studies that include food loss inside system boundaries find that even a moderate loss can have noticeable consequences on product life cycle performance (e.g., [29,31,49]). Few studies, however, account for product losses in the analysis, despite their potential importance. Future life cycle assessments evaluating alternative packaging designs should therefore take product losses into account—or justify their exclusion (even if because including loss or the product is simply not feasible)—in order to capture the full life cycle burdens, especially when the designs are empirically associated with different product loss rates and when environmental impact associated with these losses is expected to exceed packaging impact.

5.2 What is the intersection of the waste management hierarchy and LCA results?

Depending on the waste infrastructure in their region, consumers may view packaging as a key environmental concern due to the perception of packaging as a waste that builds up in landfills. The general public is also increasingly concerned with packaging waste contributing to litter as well as to marine debris [50]. The waste management hierarchy (Figure 5-2, p.25)

Box 2: More than just packaging

Feeding a growing and increasingly affluent global population—and doing so in ways that are environmentally and socially sustainable—is one of the challenges facing global society today. Food waste is a key issue of concern in both developed and developing economies and one that will have to be addressed if we are to make better use of natural resources and alleviate hunger. Challenges and solutions will differ, though as upwards of 40% of food waste in industrialized nations occurs at retail or with the consumer[a], whereas as much as 90% of food loss in developing economies occurs in the field, during transport or storage, or at retail[b]. Packaging solutions can help improve food availability and reduce loss, particularly in developing economies. By protecting and preserving food that is grown in increasingly distant locations, packaging can also prolong shelf life and enable retailers to offer consumers a wide variety of fresh produce and other food[c].

Packaging, however, is not the only solution to ensuring food availability and accessibility, nor will improved packaging alone solve our problems. Food and beverage packaging, while a large industry in its own right, is only one of the many stakeholders in the larger food and beverage industry. Industry players will need to work together to ensure that food is not only efficiently grown and harvested, but also distributed and accessible for consumption. Solutions will span the whole value chain, from increasing field productivity to building necessary infrastructure for transportation and storage. Even consumers and retailers will have to play a role in reducing food loss. Wasted food represents wasted energy, water, and financial resources. US consumers, for instance, spend around 7% of their income on food[d], of which they dispose approximately 25%, representing losses of $1,350 to $2,275 for the average family of four[e]. Consumers in developing countries, on the other hand, spend around 70% of their income on food[d] and dispose around 10 times less (by mass) than the average US consumer[e]; food waste in these areas occurs mostly in the supply chain, as stated above. Packaging, while important, will only get us part of the way there to feeding the world: we need to reduce waste and use resources more efficiently. Life cycle assessment can guide us on this path, but LCA studies on introducing packaging to improve food availability and to prevent food losses are still missing and so the implications of this issue could not be formally assessed in this knowledge mining effort.

a. J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck, *Global food losses and food waste*, Rome, Italy: Food and Agriculture Organization of the United Nations, 2011.

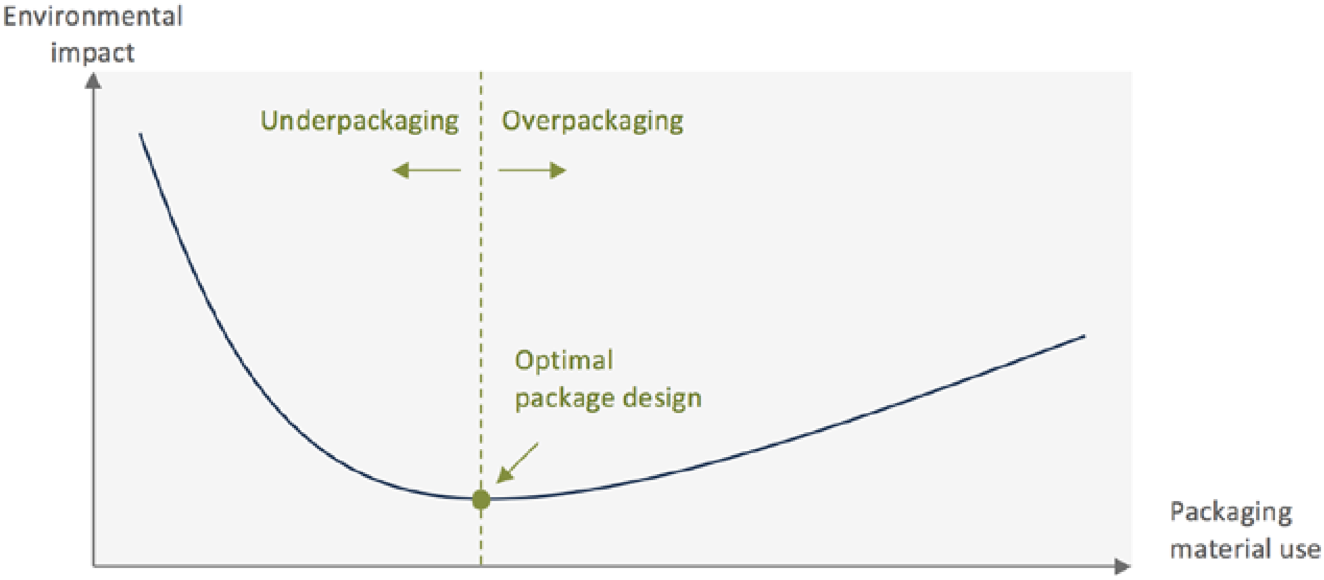
b. W. Moomaw, T. Griffin, K. Kurczak, and J. Lomax (2012). *The Critical Role of Global Food Consumption Patterns in Achieving Sustainable Food Systems and Food for All*, A UNEP Discussion Paper, United Nations Environment Programme, Division of Technology, Industry and Economics, Paris, France.

c. J. Lundqvist, C. de Fraiture, and D. Molden, *Saving Water: From Field to Fork - Curbing losses and wastage in the food chain*, SIWI, 2008.

d. A. Steiner, J. Graziano da Silva, press conference of the launch of the Think – Eat – Save campaign of UNEP and FAO, Geneva, Switzerland, 22 Jan 2013

e. D. Gunders, Wasted: *How America Is Losing Up to 40 Percent of Its Food from Farm to Fork to Landfill*, National Resources Defense Council, 2012.

Figure 5-1: Minimizing product and package system environmental impact



Sources:
EUROPEN and ECR Europe, Packaging in the Sustainability Agenda: A Guide for Corporate Decision Makers, 2009.
Flexible Packaging Europe, "The Perfect Fit: Flexible solutions for a more sustainable packaging industry," 2011.

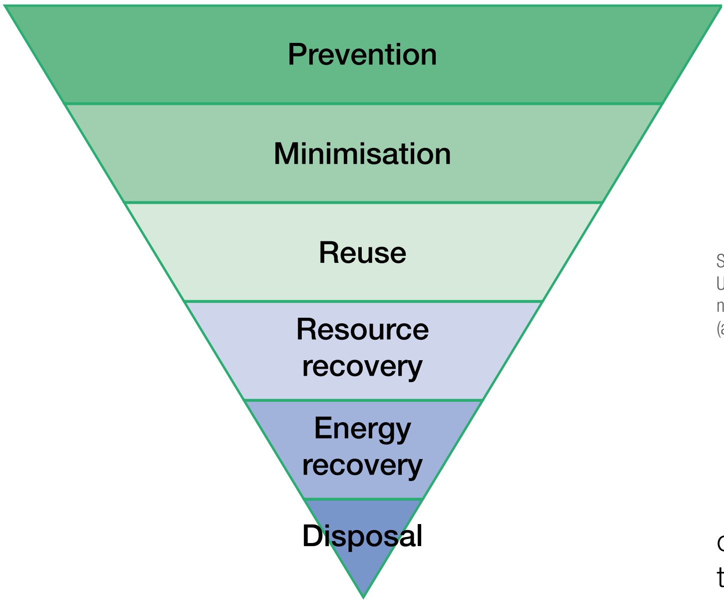
is used by many governments and businesses to inform decisions as it provides guidance to reduce packaging waste by listing the order of preference of end-of-life pathways. Knowledge mining results demonstrate, however, that the order in which the hierarchy specifies these pathways aims to minimize landfill use specifically, and consequently does not always align with preference as determined using LCA, which aims to minimize environmental burdens beyond waste[16]. Several authorities who make use of LCA for governmental policymaking, including European authorities, recognize this and therefore rely on the hierarchy for guidance, but allow deviations when they lead to broader improved environmental performance. Thus, while the hierarchy is a helpful and straightforward approach to decision-making, strictly following it may not lead decision makers to the packaging design with the lowest overall environmental burden on metrics like global warming potential, primary energy demand, acidification.

A comparison of LCA outcomes and waste management hierarchy guidance indicates the hierarchy is often, but not always, appropriate for single-material analyses, in which alternative packaging designs made from the same material are compared (e.g., a glass bottle versus another, differently-shaped glass bottle with the same volume), but may not be applicable to cross-material comparisons, in which alternative designs are manufactured from different materials (e.g., a glass bottle versus a plastic bottle). Therefore, it is important that designers or policymakers do not take actions that apply the framework universally. Both the hierarchy and LCA can lead to the same order of preference when it comes to dematerialization or avoiding use of resources—assuming, of course, that total resource use is minimized and the burdens are not shifted from the packaging to the product. The waste management hierarchy, for example, promotes package reuse over material recycling, incineration, and landfilling. In cases where reusable and single-use packages are manufactured from the ***same*** material, the former is likely to have lower impact per use than the latter because only one package need be manufactured, the environmental burdens of which are allocated over the multiple uses. An analysis comparing returnable glass versus single-use glass beer bottles illustrates this point and concludes that the returnable bottles are associated with lower impact even after accounting for damaged and disposed bottles [15]. The waste management hierarchy can also be applicable to cross-material comparisons, as an analysis of packaging for fruit and vegetable transport shows [17]: the reusable package can have lower environmental burdens than a single-use package.

The waste management hierarchy, however, is not appropriate for all single-material or most cross-material comparisons and thus should be

16 It should be noted that LCA models of landfills often have shortcomings in that they do not account for all landfill emissions—both short and long-term—particularly in models that contain organic carbon materials.

Figure 5-2: Waste management hierarchy



Source:
US EPA, Solid Waste Management Hierarchy, 2012. Available from: http://www.epa.gov/osw/nonhaz/municipal/hierarchy.htm
(accessed 2013-Jan-15)

applied with caution. The hierarchy is a "rule of thumb" and may need to be validated through a thorough LCA. Additionally, it is worth noting that minimizing environmental burdens and landfill use are not the only factors decision makers have to consider during the packaging design process: cost obviously plays a role, as do supply chain and manufacturing considerations.

For example, a comparison of a returnable glass versus a single-use plastic bottle in terms of ideal end-of-life scenario is more complex. Indeed, it may be necessary to conduct an LCA to validate that a particular disposal pathway leads to the lowest environmental burdens. For instance, LCA results indicate that significantly higher burdens associated with the raw materials, production, or use (i.e. cleaning) stages of a reusable package can potentially negate any benefits realized from reusing the package (e.g., [19,20]). Similarly, some LCA studies support preference for recycling over energy recovery or landfill disposal, while others indicate that some packaging designs, even though not recyclable, nonetheless reduce environmental burdens through lower material use and thus lead to lower impact than recyclable designs (see [3–6] for examples of both). LCA represents the appropriate tool for such cross-material analyses: in such cases, relying solely on the waste management hierarchy may be insufficient.

Additionally, at any point in time, there exists an optimal recycling rate for each material at which the resources and emissions associated with collecting the marginal package may outweigh the benefit of recycling that package. This rate will depend on collection system logistics, secondary material production losses, resources and emissions associated with primary material production, and resources and emissions associated with recovered waste processing and share of energy recovered and sold [51–54]. Indeed, these factors and resources and emissions associated with waste processing will ultimately determine the preferred disposal pathway—recycling, incineration, or landfill—for a particular material [55,56]. The final decision on optimal end of life pathway, like with any packaging decision, would include performance, costs, reliability and environment, though these attributes were outside the scope of this project. With numerous factors affecting environmental burdens, it may not be possible to identify a single best disposal route by material independent of its specific application.

Thus, there is not one approach that always optimizes for a broader spectrum of environmental impacts beyond reducing waste to landfill: conclusions ultimately depend on the system under study, packaging materials considered, packaging disposal pathway, and so forth. This context-dependence is illustrated in a study [18], in which reusable drinking cups are associated with a lower environmental burden in the majority of categories under one set of conditions, but a higher burden in most categories under alternative conditions.

Ultimately, both the waste management hierarchy and LCA have their respective contributions in leading decision makers to the best option for multiple stakeholders.

6. Implications for Packaging Design

6

This chapter outlines the implications of learnings for packaging designers in order to avoid shifting environmental burdens from one life cycle stage to another or from one environmental concern to another, and to drive meaningful reductions in the strategic environmental priorities.

The key elements of applying a life cycle approach to packaging design significantly resemble basic "good design" principles in traditional packaging design. Key principles include:

- **Optimize efficiency and effectiveness of packaging, keeping the product at the forefront.** The nature of the packaging supply chain is such that there may be a separation between the raw material provider, packaging converter, and food or beverage processer, which can lead to missed opportunities in the optimization of the collective package and product system. Designers aiming to develop packaging with reduced environmental burdens in this value chain, however, must resist the temptation to optimize only for materials, distribution, or end-of-life and instead address the full cradle-to-grave package and product life cycle as a way to differentiate the more environmentally sound alternative. Regardless of the material choices in packaging design, the product packaging with the highest environmental burden is one that is either underpackaged, enabling breakage or theft, or overpackaged, requiring more material, and therefore burden, than is necessary. Designs must strive for the optimum package design, as illustrated in Figure 5-1.
- Expand the tool box. Both life cycle thinking, where the general principles outlined above are applied, and life cycle assessment, where a quantitative evaluation is conducted in order to demonstrate the outcomes of application of these principles, are useful tools for the packaging designer for making optimal decisions around multiple priorities.
- Initiate design with a material-neutral perspective. Because there is no material that is environmentally benign in every application and for every life cycle stage in every impact category, optimizing the environmental performance of a package design must begin without predisposition on the more "environmentally responsible" material.
- **Account for multiple attributes simultaneously.** Consider a comprehensive set of environmental metrics over the complete life cycle of the packaging materials and manufacturing, the potential product to be included, as well as the performance of the package design. Simple proxies such "recyclability" or "renewable content" may help guide the way to narrow down the number of design options, but do not guarantee lower environmental burdens as some studies have shown.
- **Conduct life cycle assessments when appropriate.** It is important to be mindful of when it is critical to quantify design scenarios to inform a final decision on a packaging design—and when LCA is the right tool. For example, customer requests for a carbon footprint, comparisons with competitors, or evaluations of significantly different design concepts will often require a formal assessment. An expedited LCA is a possible alternative to a detailed ISO-compliant analysis in many cases. Many tools are available to do high quality, but expedited, LCAs for a non-expert audience for these purposes. In other scenarios, different assessment tools may be necessary to address other environmental, social, or economic impacts of interest.
- **Make informed trade-offs.** Designing to improve the environmental performance of packaging sometimes requires trade-offs between various indicators of importance as quantified by LCA. There is no absolute approach to balancing these trade-offs; other functions of packaging (e.g., communication of nutrition information) as well as commitments and business priorities of the organization, brand, or product family will also contribute to guide the final decision. The key message from this analysis is that to avoid unintended consequences, it is critical to be aware when these trade-offs are being made.

7. Implications for Governmental Policymaking

7

This chapter discusses the implications of the knowledge mining results to governmental policymaking that affects packaging. Typical policy areas where a life cycle approach is valuable include: product policies (like integrated product policy), packaging and packaging waste policies, general waste policies, environmental & resource efficiency policies, environmental labeling schemes, environmental communication and education, research programs in the area of products and packaging development and design, among others.

Often an objective of any policymaking related to environmental sustainability is to drive a reduction in impact, directly, or drive a change in behavior to reduce impact indirectly, while maintaining performance and price competitiveness. A life cycle approach offers policymakers a lens to develop policies that enable the organization to achieve its ultimate objective—reductions in impact—by enabling policymakers to evaluate the root causes of environmental problems like climate change, water stress, eutrophication, and other environmental impacts from manufacturing, trading, consuming and disposing of products. This understanding identifies the most effective leverage point for achieving reduction in overall impact.

However, taking a life cycle approach does not require a life cycle assessment for every decision. If a policy is built based on the strategic priorities of the municipality, which are themselves informed by solid science and other considerations, informed policy can be executed without completing product LCAs. For example, the EU utilizes the waste hierarchy as a rule of thumb for the region's governmental policymaking, but also acknowledges that deviations can be justified if they lead to an overall reduction of environmental impacts.

The results from mining other life cycle assessment literature are an important place to start to incorporate life cycle thinking into packaging policies. As illustrated through the findings of this knowledge mining exercise, the following principles are critical elements of policymaking that takes a life cycle perspective to food and beverage packaging:

- Address the root causes of environmental problems. The findings from the literature considered in this report indicate that packaging for food products typically—but not always—has a relatively smaller impact than the packaged product itself (see Section 5.1.3). Packaging policies or policies that address both the product and packaging, when attempting to optimize environmental impacts, therefore need to be able to acknowledge that the package itself or waste management of the package may not be the key driver of environmental impact. The impacts associated with agricultural supply chains, particularly for complex products with many ingredients, can be higher than the impact of the packaging (e.g., [30,41]). This increases the importance for the packaging to sufficiently protect and preserve the food product. For beverages, the impact of the packaging varies more depending on the type of the beverage. Waste management after consumption may be the exception to this rule of thumb, but optimizing for municipal waste management likewise cannot be done in a vacuum.

  These policies must also balance specific environmental goals with protecting food and beverages from damage or spoilage—recognizing that these goals and appropriate solutions may differ depending on region and level of government. As an example, food losses in developing economies occur at different points in the supply chain compared to losses in developed countries (e.g., see [57]); thus, policies reducing loss through packaging or other means should first acknowledge root causes of impact and work to address those.
- Identify policy objectives. The overall objectives of local governments should guide policies related to the reduction of impacts

from food and beverage packaging. A municipality may have to balance packaging environmental impact with other priorities or concerns of communities (e.g., availability or accessibility of waste management infrastructure), which would influence the nature of the policy inherently and inform how to manage trade-offs.

- Incorporate regional variations in policies. Effective packaging policies will recognize that regional variations may be necessary given differences in waste infrastructures. Objectives may differ depending on whether the policy governs operations at a local level or at a national level. For instance, a municipality may wish to minimize waste in order to lower disposal costs, whereas a federal government may seek to reduce environmental impact. Even at the same regional scale, preference for a particular waste management practice based on LCA result can differ among regions due to variation in local conditions. For example, requiring that packaging not use chlorine-containing materials may be more relevant to municipalities that incinerate their waste for energy recovery compared to those that invest in landfilling or material recycling.
- Create material-neutral policies. Life cycle assessment information gives governments the data needed to create policies that drive improvement across multiple attributes or to recognize the trade-offs associated with a certain material or design choices. A single material or design choice rarely offers the lowest environmental impact across all life cycle stages (see Section 5.1.1), in all circumstances. Therefore, optimal policies may need to be material- or design concept-neutral to ensure that packaging designers assess the trade-offs associated with different materials.
- Link policies to broader environmental priorities. Successful packaging policies link back to the overarching environmental improvement priorities of the organization making the policy. Setting policies that fit within broader goals ensure that all facets of the organization make decisions with the overall goal of meeting the same targets. Policymakers should consider the environmental objectives of their larger organization as a guidepost for their packaging-related policies
- Apply policy to guide environmental trade-offs. Designing for packaging with reduced environmental burden sometimes requires trade-offs among various indicators of importance. Environmental policies of governments should therefore provide guidance in balancing these environmental trade-offs. The key message from this analysis is that it is critical to be aware when these trade-offs are being made, and that they are made in line with the governmental environmental policy to avoid unintended consequences or consequences contradicting the official policy.

In sum, a life cycle approach can easily be incorporated into the policymaking process. First, life cycle thinking can impact how problems or goals are identified as it allows policymakers to understand environmental problems in a holistic manner. Once policymakers have identified potential policy solutions, life cycle thinking or LCA can be incorporated into any type of cost/benefit analysis used to assess which policies offer the most benefits financially and also environmentally. This is not to say that LCA should be used for every policy or every product, but rather as a means to identify environmental hotspots or otherwise better inform the decision and ensure the burdens are not shifted elsewhere. Lastly, life cycle thinking related to potential policies can be shared with stakeholders as policymakers engage with those who are likely impacted by the policy (in the case of packaging, designers and product development teams).

8. Implications for Conducting an LCA for Food & Beverage Packaging

8

This section aims to leverage insights from this knowledge mining exercise in order to provide guidance to practitioners and commissioners of future food and beverage packaging life cycle assessments. Shortfalls and gaps, as well as positive aspects, of the mined studies were used to develop guidance on improving future LCAs of food and beverage packaging. LCA development for the express purpose of supporting knowledge mining efforts is, at best, a by-product of this guidance and rarely—if ever—should be the primary goal of conducting LCAs. The objectives of conducting an LCA, rather, should be defined by the practitioner or commissioner when they define the goal and scope of the study per ISO standards.

The use of life cycle assessment to quantify the environmental impacts of food and beverage packaging systems helps to:

- Ensure that opportunities to reduce the overall environmental impact (avoiding burden shifting between impact categories or life cycle stages) are identified
- Compare alternative packaging designs and understand trade-offs
- Ensure that the study results are representative of the packaging systems evaluated in the analysis.

These points are consistent with the outcomes of the knowledge mining exercise. Exercise results are used to inform guidance on how to set up and conduct a food and beverage packaging LCA that provides useful insights into the environmental impacts and forms the basis for product improvements, for decisions related to suppliers or raw materials, or for environmental policy measures of local or national governments. Not discussed in detail are the basics of conducting an LCA; for readers interested in learning more, general information on LCA is available[17,18].

- **Conduct life cycle assessments when appropriate.** Life cycle assessment is a framework to quantify the environmental impact of a product or system. Depending on goals or objectives, LCA may or may not be the appropriate tool to inform a decision. Packaging design properties, for instance, can potentially serve as proxies for environmental performance, but before using them, the practitioner will need to show that improvements in these metrics do indeed translate to reduction in environmental burdens over time. Additionally, the waste management hierarchy can provide decision-

17 J. Fava and J. Hall, Why Take a Life Cycle Approach?, UNEP/SETAC Life Cycle Initiative, 2004.
18 Life Cycle Management: How business uses it to decrease footprint, create opportunities and make value chains more sustainable, UNEP/SETAC Life Cycle Initiative, 2009.

making guidance, but one should keep in mind that the aim of this tool is to save resources and to minimize landfill waste. LCA, by contrast, focuses on environmental burdens beyond resources and waste; thus, decisions made using LCA can potentially lead to different results than those made using the waste management hierarchy. If conducting an LCA is appropriate, it is strongly advisable to follow the ISO standards 14040 and 14044[19,20] when undertaking the analysis. These standards also specify the requirements regarding communication of LCA results to third parties. Specifically, they require making an LCA report available to these third parties, as well as transparent reporting while respecting confidentiality, as outlined in ISO 14044, Section 5.2. In the case of comparative assertions made public, the critical review report must also be available. Any further communication should stick to the ISO requirements regarding reporting to stay aligned with the complete findings and conclusions of the LCA and to avoid biased communication.

- Clearly articulate the goal of the study. LCAs of food and beverage packaging options may be pursued for different goals, such as to drive improvements in future packaging designs or future package-product systems, to understand differences in environmental performance of alternative packaging designs fulfilling the same function, or to compare different packaging end-of-life treatment options. Another focus may be on the relevance of packaging in a product's life cycle. Some studies focus on packaging only; others take the product to be packaged into account. The goal of the study may directly influence the scope of the LCA; thus a clear definition of the goal helps to tailor the necessary scope of the LCA study and to optimize the efforts needed to carry out the LCA.

19 ISO, Environmental management — Life cycle assessment — Principles and framework, 14040:2006.
20 ISO, Environmental management — Life cycle assessment — Requirements and guidelines, 14044:2006.

- Describe the object of investigation in detail. Some context about surrounding use or additional functions is necessary and may influence decisions, e.g. the preference for a certain type of cup depends on the number of people attending a catered event at which the cups are used [18]. Packaging designs need to be defined clearly, especially in packaging comparisons, in order to determine material and energy consumption required to produce the package.
- Understand implications of the functional unit choice and account for real-life conditions. The functional unit is defined in terms of system function (e.g., providing packaging for a certain volume, mass, or no. of servings), quantity & unit (e.g., 1,000 ounces, liters, grams, count), duration (e.g., desired shelf life), and level of quality (e.g., shelf space dimensions, air and/or moisture tightness, resistance to pressure, scratches, abrasion, or impact, etc.). While the first three directly influence the calculation of the packaging and product masses (i.e., the reference flows) per product system, differences in the latter may only be discussed qualitatively. The choice of functional unit can also influence whether food waste and

consumer behavior need to be included in study scope. For example, "the packaging required to deliver 1,000 liters of product to the consumer" as a functional unit may only need to account for retail losses, whereas "the packaging required to deliver 1,000 liters of product for consumption by the consumer" not only needs to account for retail losses, but also for consumer losses, which are influenced by consumer behavior.

Regardless, functional units should be defined taking into account real life conditions: packaging systems should be investigated in a comparison of different packaging options and products should be considered in case the relevance of packaging in a food or beverage product's life cycle is of interest. When conducting a comparative assessment, it should be ensured that the alternative packaging designs fulfill the same function.

- **Consider all life cycle stages in an analysis or justify exclusions.** A perspective that accounts for all life cycle stages of a product or package is recommended although on occasion, a more restricted scope can be useful. A cradle-to-grave analysis for packaging adopts this perspective, as does a cradle-to-consumer analysis for food or beverage products. By contrast, a cradle-to-shelf analysis is similar to a cradle-to- gate evaluation although in the former, distribution to retailer is considered. If a restricted scope such as cradle-to-gate is used, the choice of system boundaries should be justified (i.e. other phases are identical or negligible for all alternatives) and the practitioner should clearly acknowledge which life cycle stages are included and which are excluded.

- **Account for all differences in packaging designs.** If packaging options are expected to differ in the amount of distribution and product losses, the food or beverage lost should be included in the analysis for each packaging design to ensure the burdens are not shifted from packaging to product. Product losses can be due to filling losses at the food producer, distribution losses (e.g., the new design is more durable), retail losses (e.g., more breakage), and consumer losses (e.g., less product wasted). If a package design also enables changes in the product's recipe or formulation (or vice versa), the product itself should be included. Either way, justification is necessary, in case food or beverage losses and other potentially relevant aspects are excluded from the analysis.

  Differences in distribution can arise, for example, if a packaging designer is able to reduce primary package volume so that while it contains the same amount of product, more packages fit on a pallet. If competing packaging options are analyzed, space utilization needs to be considered. In case different packaging options require different ways of distribution (e.g. chilled, frozen, or ambient distribution), differences in the product, energy consumption, and food losses need to be accounted for.

- **Account for regional variation in packaging disposal analyses.** The disposal scenario should reflect the consumer's geographic location. For products delivered to multiple locations, an average disposal scenario reflecting the multiple locations may have to be defined. If important, some distinct scenarios (e.g., 100% recycled, 100% landfilled, 100% incinerated, etc.) may be modeled in sensitivity analyses. These additional scenarios would allow study readers to choose which scenario best represents their local situation and extrapolate results to understand the consequences in potential future scenarios.

- Consider a variety of inventory metrics and impact categories. This is especially important when the product losses are included in the analysis. For example, a study about the Stonyfield Farm [43] shows that focusing on energy or climate change may result in increased damages in water quality or toxicity.

  If agricultural processes are included in the system boundaries, at a minimum eutrophication, acidification, water use, and land use should be assessed next to climate change and primary energy consumption. However, additional indicators as photochemical oxidant formation, abiotic depletion of resources, and toxicity may strengthen the study's conclusions. Ultimately, it is up to the practitioner to choose which impact categories to analyze and, in an ISO-compliant LCA, present his reasons for including or excluding categories.

  Several methodologies are available for calculating impact category results. Example methodologies include the characterization models used in TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and other environmental Impacts)[21], ReCiPe[22], CML 2001, Impact 2002+, LIME (Life-cycle Impact assessment Method based on Endpoint modeling), and ecological scarcity 2006[23].

- Explicitly mention and justify end-of-life allocation approach for recycled packaging. Numerous options for allocation have been defined by the LCA community. Avoided burden (a.k.a. end-of-life recycling) and the

21 J. Bare, "TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0," Clean Technologies and Environmental Policy, 13:5, p. 687, 2011.
22 M. Goedkoop et al., "ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level", 2006. Available from: www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf (accessed 2013-Jan-14).
23 R. Frischknecht, R. Steiner, and N. Jungbluth. The Ecological Scarcity Method - Eco-Factors 2006: A method for impact assessment in LCA. Federal Office for the Environment FOEN, Zürich und Bern, 2009. Available from: www.bafu.admin.ch/publikationen/publikation/01031/index.html?lang=en (accessed 2012-Feb-12)

recycled content (a.k.a. cut-off) represent two common allocation approaches. In studies that follow the avoided burden approach, credits for avoiding primary material production are given to the product system which itself is recycled. By doing this, the credited burden is allocated to the subsequent product system's life cycle. Energy recovery from incineration and landfill gas collection is similarly addressed: the product system receives the burdens for landfill or incineration of waste, but is credited for avoiding electricity generation or thermal energy production. Energy credits are typically based on the country average grid mix or thermal energy production from fossil fuels. With the recycled content approach, material scraps to be recycled leave the system with neither burdens nor credits. Materials made from secondary raw materials bear only the burden of scrap collection, sorting, and refining. This gives an incentive to use recycled materials in the product systems under study. Also under this approach, the product system is assigned the burden of landfill or incineration of waste, but energy recovered from waste processing is "cut-off" and thus leaves the system with neither burdens nor credits.

While these two allocation approaches may result in opposite results[24], there is no one "correct" answer when choosing how to allocate burdens among product life cycles. Likely, the preferred approach will depend mainly on the practitioner's value judgment. If the allocation approaches influence the results substantially, a sensitivity analysis covering different allocation procedures should be performed.[25,26]

- **Ensure high data quality for processes and emissions that contribute substantially to the overall environmental impacts.** In the case of food and beverage packaging LCAs, such processes will typically include packaging material production and converting and potentially food losses (see Sections 5.1.3). Additionally, if a particular emission is seen to drive one or more impact categories (e.g., nitrous oxide affects both climate change and eutrophication), the emission factors (in this example, the mass of nitrogen oxide per unit of manufacturing or transport service) will ideally be of high quality. Sensitivity analyses and uncertainty assessments are recommended approaches to show the robustness of results of an LCA study.
- **Identify the target audience to guide the analysis.** The LCA results may be addressed to packaging designers and food and beverage processers (to foster environmentally improved packaging solutions), to the public (to increase awareness about either environmentally preferable packaging options or about the role of packaging with regard to the environmental impacts of food and beverages), as well as to public policy makers (to validate environmentally motivated waste policies). The LCA results may be addressed internally (within a company) or externally.
- **Use LCA results to make informed trade-offs.** The interpretation of results and the conclusions are straightforward if and when the LCA shows lower life cycle environmental impacts of one packaging options with regard to all indicators considered and the sensitivity analyses do not challenge these results. Unfortunately, this is not the most common case. It is important to point to contradicting results and their reasons. Trade-offs should be made explicit. Data quality aspects and the scope within which the findings are valid should be reflected and mentioned when formulating recommendations.

24 R. Frischknecht, "LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency," *The International Journal of Life Cycle Assessment*, vol. 15, Jun. 2010, pp. 666–671.
25 ISO, Environmental management — Life cycle assessment — Principles and framework, 14040:2006.
26 ISO, Environmental management — Life cycle assessment — Requirements and guidelines, 14044:2006.

9. Conclusions

Environmental performance in packaging is a multi-faceted issue with many interested and affected parties. Balancing the performance, cost, and environmental efficiency of packaging therefore requires a holistic evaluation. The systematic review of existing LCA studies in the food and beverage packaging industry demonstrated both the value of taking a life cycle approach as well as specific aspects of this approach. It also indicated that environmental performance in packaging can be understood quite effectively through the application of LCA. Many LCAs exist that analyze packaging for food and beverage products; this project was conducted to consolidate existing knowledge and facilitate decision making in which packaging environmental effectiveness and efficiency is optimized based on a life cycle approach. As a result, this analysis provides decision makers with a solid foundation of support for their packaging-related decisions including environmental aspects by leveraging a much larger body of work.

Through applying knowledge mining, this study validates some basic principles of life cycle assessment through meta-analysis and begins to extrapolate the implications of these principles for key decision makers. Key learnings from knowledge mining included:

- Life Cycle Assessment helps encourage a transition away from focus on single-issue environmental priorities and provide insurance that environmental burdens are not shifted from one life cycle stage to another (e.g., from manufacturing to raw material production). In other words, LCA results make it more difficult to make decisions that are out of context for the product or environmental impacts being optimized.
- There are few, if any, generalities about what makes a package environmentally preferable in terms of materials or design attributes; LCA provides a standardized and objective framework for conducting such evaluations and comparisons. The optimal packaging design from an environmental performance standpoint will vary according to packaging system characteristics such as raw materials chosen for use, the specific product being packaged, and the corresponding supply chain.
- A detailed cradle-to-grave LCA may not be required for every type of decision to be made about packaging design, manufacturing, and governmental policymaking. Qualitative consideration of the broader life cycle may be sufficient to guide many decisions, and streamlined LCA tools are available for high level analyses.
- LCA is a highly valuable tool in driving more environmentally preferable packaging, and can be supplemented by other tools to measure other important economic, technical, or social characteristics depending on the objectives and values of the user.
- LCA is a tool that can be used to support decision making by providing environmental data and information. Ultimately, it is the decision maker's responsibility to decide which metrics should factor into the decision and how to address any trade-offs among alternatives. Additionally, LCA quantifies environmental performance; risk assessment and social sustainability are two examples of business concerns that cannot be addressed with LCA.
- The waste management hierarchy can be a good rule of thumb for directional evaluations and can give appropriate recommendations in specific cases (e.g., single-material analyses), but may not be appropriate for comparisons involving packaging designs manufactured from different materials (e.g., glass versus plastic).

While some of these learnings will not be news to the LCA community, validating the intuition of the community through a rigorous analysis brings credence to a larger audience to the basic principles of life cycle assessment when applied to packaging. In addition, these validated approaches can be put to immediate use amongst three major practitioner groups in the value chain of packaging for food and beverage: packaging designers, LCA practitioners, and governmental policy- and decision-makers. Examples of practical implications include the following:

- When designing packaging and governmental policy, it is critical to keep in mind packaging's primary purpose of product protection when seeking to optimize the efficiency and effectiveness of packaging.
- Conduct life cycle assessments when appropriate. In cases when an LCA is necessary, the analysis should account for all differences in packaging designs, such as product loss or more efficient cube utilization.
- Trade-offs among environmental indicators as quantified by LCA and other commitments and business priorities are often required; it is important to be fully informed about these trade-offs when making design and policy decisions.
- Design governmental policies that do not favor one material or design attribute over another, but rather aim to achieve a desired environmental outcome (e.g., reduced greenhouse gas emissions) and allow the packaging decision maker to choose the optimal material.
- Identify governmental policy objectives that link to broader environmental priorities of the government or policymaking body. The resulting policy should align with government or organization goals and address the root causes of environmental impacts of packaging systems rather than target "superficial fixes".
- Incorporate regional variations to account for differences in culture and consumer behavior, waste infrastructure, and local government objectives.

A secondary goal of this study was to develop a generalizable knowledge mining methodology that could be applied beyond LCA or packaging. The knowledge mining methodology, developed for this analysis, can be applied more broadly to other areas of research.

9.1 Future Research

Given the foundation laid in this study, a number of next steps could be taken to further the research topics—namely, knowledge mining, life cycle assessment, and food and beverage packaging—addressed in this study. Possible future research includes:

- **Expand the knowledge mining methodology to include studies beyond LCAs.** Although the proposed knowledge mining methodology was tailored specifically to mining LCA literature, it is meant to be a more generalizable concept for systematically reviewing information and gathering key insights. Future knowledge mining exercises could therefore investigate how qualitative literature could be used in support for adopting a life cycle perspective of a product system or, more generally life cycle thinking beyond the environmental perspective LCA brings to the table.
- **Conduct data mining to inform further decision-making.** This study focused on a meta-analysis of knowledge and outcomes from LCA; quantitative meta-assessments of LCA data and results were considered beyond current study scope. Therefore, quantitatively mining actual results to define specific characteristics of packaging designs and their likely environmental implications, similar to NREL's data mining studies on power generation[27], could be valuable for decision-makers of various types. Such analyses could also be used to supplement knowledge mining exercises.
- **Investigate the role of LCA in addressing national or global level issues.** LCAs are often conducted from a product perspective

27 See, among others, M. Whitaker, G. A. Heath, P. O'Donoughue, and M. Vorum, "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation : Systematic Review and Harmonization," *J Ind. Econ.* 16, 2012 Apr, pp. S53-S72.

and thus do not address broader sustainability issues such as climate change policy, resource conservation, food waste, or economic development at ”macro” levels. Thus, a study along these lines could illustrate the value of LCA or other methodologies in answering questions at a national or global level. In particular, such an analysis could identify any potential differences or special considerations that would be necessary to strive towards sustainability objectives defined at a national or global level.[28]

- **Evaluate the extent of differences in LCAs conducted for OECD countries versus developing economies.** Although it was postulated in this report that the methodology is the same but that goals and practical implications may differ, it was not possible to concretely support these statements with knowledge mining outcomes. Thus, future LCA or knowledge mining research could investigate the effect of regional differences on LCAs or, more generally, on the product system or other topic of interest.
- **Understand the influence of LCA-derived messaging on consumer behavior.** This study illustrates the value to a packaging designer of adopting a life cycle approach and conducting LCA to better inform design decisions. However, the value to a packaging manufacturer, food processor, or other company of being able to use LCA results to support marketing and other messages is not well understood or measured. It would therefore be worthwhile to investigate whether messages derived from LCA results do indeed influence consumer behavior or to what extent consumers have changed their habits based on a better understanding of product or packaging environmental impact.
- **Evaluate the “intangible” value of LCA-driven decisions to a product manufacturer.** By using LCA to inform design decisions, a product manufacturer is potentially able to reduce costs and improve a product’s environmental performance, in addition to creating sustainability-related value to customers. There are also intangible benefits from incorporating LCA into the design process and, more generally, defining and implementing a sustainability strategy—benefits such as improved reputation among stakeholders and clients, and a larger and stronger hiring pool for job applications.
- **Quantify the environmental benefits of the function of food and beverage packaging itself.** Given the growing extent of global food loss, it would be valuable to quantify the benefits of the protection provided by packaging and how having this protection helps reduce food loss and the environmental impacts associated with wasted food. Real life experiences are required to establish a potential correlation between packaging on one hand and the prevention of food losses by this packaging on the other. LCA is then one means to evaluate the impact of wasted food and can help better inform packaging design decisions, albeit from an environmental perspective. Other methodologies can be drawn upon to evaluate the social perspective of food loss and the benefits of packaging.
- **Understand the implications to small and medium sized enterprises (SMEs).** In contrast to large enterprises in the packaging and food value chain, smaller players often have to address different or additional challenges. For instance, SMEs often do not have the resources or internal demand for a dedicated LCA practitioner or other environmental sustainability resource. Therefore it may be worthwhile to understand the implications of imposing LCA or other time- and resource-intensive requirements on their businesses in order to minimize unintended consequences.

28 An initial assessment of the environmental impact of grocery products, Product Sustainability Forum, Final Report, Project code: RPD002-004, March 2013, 132 pages.

Appendices

Appendix A: List of Acronyms

AP	Acidification Potential
EIO-LCA	Economic Input-Output Life Cycle Assessment
EP	Eutrophication Potential
GHG	Greenhouse Gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCT	Life Cycle Thinking
MFA	Material Flow Analysis
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
SETAC	Society of Environmental Toxicology and Chemistry
SFP	Smog Formation Potential
UNEP	United Nations Environment Programme

Appendix B: Glossary

Acidification Potential (AP): A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.

Attribute Matrix: Matrix used in this report's knowledge mining to systematically organize and document studies. Study details recorded include publication information, LCA details, key points, and contribution to research question answers.

Characterization Factor: Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator (e.g. for global warming potential, each greenhouse gas is assigned a factor of x kg CO_2-equivalents per kg gas). [ISO 14044:20067]

Converting: Production of finished packaging for filling and distribution.

Cradle-to-Grave LCA: Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end-of-life.

Cradle-to-Gate LCA: Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) associated with a product's life cycle from raw material acquisition until the end of the production process ("gate of the factory"). It may also include transportation until use phase.

Critical Review: Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment. [ISO 14040:20066]

Design-Neutral: Attribute or property that no one [packaging] design is favored over another based on design features only. The packaging with lowest environmental impacts is an example of a design-neutral property.

Emission Factor: Factor that represents the quantity of a substance emitted to air, water, or soil per unit process or activity.

End-of-Life: The final stage in a product's life cycle during which it is typically disposed via landfill or incineration, or recovered for use in another product life cycle.

Environmentally Extended Input-Output LCA: An LCA that includes not only input-output economic information (at an economic sector level), but also environmental information such as per-sector data on carbon emissions per (US) dollar spent.

Eutrophication Potential (EP): Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.

Facility: Single installation, set of installations, or production processes (stationary or mobile), which can be defined within a single geographical boundary, organizational unit or production process [ISO 14064]

Functional Unit: Quantified performance of a product system for use as a reference unit. [ISO 14040:20066]

Gate-to-Gate LCI: Addresses the raw material, working material, and energy consumption; the waste and sewage treatment service; transport service requirements; some resource inputs (such as on-site spring water or land use); and the emissions to air, water and soil related to the activities of a facility (inbound "factory gate" to outbound "factory gate").

Global Warming Potential (GWP): A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, magnifying the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.

Goal and Scope: The first of four phases, as defined by ISO 140406, in conducting a life cycle assessment. In this phase, the purpose of conducting an LCA is defined, along with the system being studied and system boundaries.

Greenhouse Gas (GHG): Gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. [ISO 14050[29]]

Hot Spot: A unit process or stage of a product life cycle that has significant potential impact on a given environmental, social or economic aspect relative to other processes or stages.

Impact Category: Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (e.g., climate change). [ISO 14044:20067]

Impact Category Indicator: Quantifiable representation of an impact category (e.g. global warming potential for climate change). [ISO 14044:20067]

Life Cycle Assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. [ISO 14040:20066]

Life Cycle Impact Assessment (LCIA): Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. [ISO 14040:20066]

Life Cycle Inventory (LCI): The step in conducting a life cycle assessment that involves data collection and modeling of the product system, as well as description and verification of data. This encompasses all data related to environmental (e.g. CO_2) and technical (e.g. intermediate chemicals) quantities for all relevant unit processes within the study boundaries that compose the product system. Examples of inputs and outputs quantities include inputs of materials, energy, chemicals and 'other' – and outputs of air emissions, water emissions or solid waste.

29 ISO, *Environmental management – Vocabulary,* 14050:2009.

Other types of exchanges or interventions such as radiation or land use can also be included. [ISO 14040:20066]

Life Cycle Stage: Component of a service or product system's life cycle (e.g., raw material production, manufacturing, use, etc.).

Life Cycle Thinking: A framework for analyzing the economic, environmental, and social performance of product systems and services over their life cycle.

Material-Neutral: Attribute or property that no one material is favored over another. The (packaging) product with lowest environmental impacts is an example of a material-neutral property.

Primary Packaging: The packaging in direct contact with the product used for sale to individual consumers. [GPPS 2.0[30]]

30 Global Packaging Project, *Global Protocol on Packaging Sustainability 2.0,* Consumer Goods Forum, 2011.

Primary Energy Demand (PED): A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, uranium etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Being the energy extracted from the earth, efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.

Raw Material: Primary or secondary material that is used to produce a product. [ISO 14040:20066]

Reference Flow: Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit. [ISO 14040:20066]

Relevance Matrix: Matrix used in this report's knowledge mining exercise to assess study quality with regard to environmental impacts covered. The matrix identifies environmental hotspots within the main economic sectors involved in the supply chain of the product group at issue based on environmentally extended input-output tables or LCA results.

Secondary Packaging: Packaging used to group primary packaging units into convenient sets for the retailer. [GPPS 2.024]

Smog Formation Potential (SFP): A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.

System Boundary: Set of criteria specifying which unit processes are part of a product system. [ISO 14040:20066]

Tertiary Packaging: Packaging, such as pallets or crates, used to group secondary packaging units to facilitate transportation. [GPPS 2.0[29]]

Appendix C: Knowledge Mining Methodology

C.1 Overview

Knowledge mining is a general concept in which a body of historical information is meta-analyzed to develop overall learnings or insights that can either reinforce or supplement currently available knowledge and literature. Knowledge mining is conducted with an end goal in mind, or in other words, a sense of the knowledge sought and the desired implications of that knowledge. In this way, it differs from a literature review, in which a practitioner aims to better understand published literature in a particular area of interest before proceeding with further research such as the definition of the research question. As such, motivations for mining knowledge and approaches for gathering information and extracting key insights will vary as objectives differ. Regardless, knowledge mining outcomes can provide guidance by leveraging existing work and allowing new research to "stand on the shoulders of giants".

The UNEP/SETAC Life Cycle Initiative aims to use knowledge mining as part of its Phase 3 strategy. To apply the general concept to the mining of knowledge from LCAs, the UNEP/SETAC Life Cycle Initiative defines the methodology as using experiences and lessons learned to provide decision-making guidance and to provide insights into important components and guidance for conducting these analyses and interpreting the results. Knowledge mining transforms data and provides insights into what components and elements are important for LCA in order to validate how LCA is done, justify the findings, and come up with new conclusions[31].

Phase 3 aims to support the mainstreaming of life cycle approaches in both the private and public sectors. One of the means to do that is to take lessons learned from over 20-years' experience in LCA and use that knowledge to develop guiding principles that enable improvements in the environmental performance of products and services. One of this project's objectives was thus to further knowledge mining within the Initiative by developing and piloting a generalizable methodology that can be applied to areas of research beyond LCA or food and beverage packaging. Although the steps outlined here were developed specifically with LCA in mind, the approach can easily be adapted to non-LCA topics.

The knowledge mining approach adopted for this study is similar to methodologies such as meta-analysis[32] and systematic review[33]. Knowledge mining outcomes are generally qualitative observations that can be used to inform future decisions and guide thinking. This is a key distinction between knowledge mining and data mining, which is often used to compile statistics and identify patterns in large sets of data—thus resulting in more quantitative outcomes. For instance, an outcome of data mining in LCA may be a number representing the average environmental burden reduction from lightweighting a package by 10%. Knowledge mining results, by contrast, may provide guidance on how to reduce the environmental impact of packaging while ensuring that product integrity is not compromised.

C.2 Methodology

In this report, knowledge mining is used to systematically document, review, and analyze food and beverage packaging LCA literature. The success of mining knowledge from literature lies in a well-structured process. This process can be divided into a preliminary and a main investigation, approximately as follows:

- Preliminary investigation
  - Define topic and articulate research questions of interest
  - Develop attribute matrix and relevance matrix to document the studies and assess study quality with regard to environmental impacts covered
- Main investigation

31 UNEP/SETAC Life Cycle Initiative, "Knowledge Mining Workshop Summary", 2011. Unpublished.

32 http://en.wikipedia.org/wiki/Meta-analysis

33 http://en.wikipedia.org/wiki/Systematic_review

    - Collect suitable literature and populate attribute matrix
    - Extract key points; expert judgment is needed to ensure key points are indeed supported by the various studies given study assumptions and results
    - Generate learnings that summarize key points
    - Qualitatively assess learnings' strengths and weaknesses given studies reviewed
- Synthesis

Iteration may be necessary to revise research questions or attribute matrix elements based on findings in new studies. The application of this methodology to food and beverage packaging is further described in Section C.3.

Since the motivation for knowledge mining, as well as the choice of research questions, direct which knowledge is mined, question choice can influence study outcomes. It thus helps to have some prior knowledge of the field before mining knowledge in order to define research questions and understand whether it is feasible to find answers. Proper framing of the research questions can also shape study results as it can affect which literature or other knowledge is mined. As such, it is recommended that individuals have some level of expertise in LCA or the topic of interest. Knowing the relevant economic sectors involved and environmental impacts caused facilitates knowledge mining in LCA. Furthermore, the rigorous application of selection criteria for LCA studies is indispensable. Finally, common conclusions and recommendations should be identified and limitations and quality of the knowledge mined should be communicated.

Publication bias needs special attention. It is often not possible to know how many studies have been conducted but never publicly published. Studies which are not publicly available may show different results from those that are. If the published studies represent a small sample of the underlying population or—more importantly—if the unpublished studies are filed away due to unfavorable results, the potential for bias in knowledge mining conclusions is high as the published studies may not be truly representative of all valid studies undertaken. Such a bias may misrepresent the results of knowledge mining of all studies (published and unpublished).

Knowledge mining also should be based on more than a few selected publications. In cases where a limited number of studies are available, care should be taken to avoid generalizing results as these results may not be broadly applicable. (And in this situation, knowledge mining may simply be unnecessary because those investigating the topic at hand can readily review the limited publications without the need for a summary document.)

For this report, no new LCAs or primary research was conducted. Instead, food and beverage packaging LCAs were leveraged in a knowledge mining exercise in order to learn from those studies how to focus and direct packaging-related conversations, better design future LCAs, and improve the information transfer among stakeholders. Other studies that qualitatively address environmental concerns or benefits of packaging were also reviewed to provide background information and supplement understanding, but learnings were based primarily on consolidated LCA results. The conclusions outline how these other issues could be evaluated further in future research in the context of reducing environmental impact. Once knowledge from the studies was consolidated, results were then used to identify trends and generate learnings about the topic of interest.

It should be noted that while knowledge mining relies on available literature, its goal is not to develop a comprehensive literature review. Secondly, only the LCAs were used to develop and support learnings; thus outcomes are limited to environmental performance insights based on LCA. Other aspects, such as social or economic performance, are not discussed.

Figure C-1: Process steps for preliminary investigation in preparation for knowledge mining

C.2.1 Preliminary Investigation

The preliminary investigation (outlined in Figure C-1) should be performed before selecting life cycle assessment studies to be mined. Firstly, the object of investigation (in this case, the environmental life cycle management of food and beverage packaging) is defined. Secondly, research questions related to the object of investigation are formulated. In a third step, the main economic sectors representing life cycle stages (i.e., agriculture, plastics, metals, transportation, etc.) involved in the supply chain of the product group under analysis are identified. The economic sectors contribute to various environmental impacts to a variable extent. These environmental impacts should be identified and the importance of the contribution of each sector estimated. It is important to understand these impacts in order to identify relevant impact categories (per the ISO standards) and ensure LCAs reviewed are accounting for these relevant categories in their impact assessment and interpretation. A qualitative relevance matrix is suggested showing economic sectors involved and their relative contribution to environmental impacts. (In the case of knowledge mining outside environmental issues, such a matrix may still be necessary in order to identify social or economic hot spots and avoid missing them while mining knowledge.) Finally, an attribute matrix is established, which allows for a systematic documentation of the studies analyzed. The next sections describe and show examples of such matrices.

C.2.1.1 Relevance Matrix

As stated in the ISO standards, an LCA practitioner is required to identify relevant impact categories for the specific product system under study and justify his choices. One of the challenges in assessing LCA study quality is how to determine whether the practitioner chose relevant impact categories—that is, do the studies indeed assess the appropriate impact categories or are key categories left out that could potentially alter conclusions if included—and do so consistently and potentially without an in-depth understanding of assumptions. In order to make this judgment, the knowledge miner needs to first know which impact categories are relevant for the product system.

We address this problem with a *relevance matrix*, which identifies relevant environmental impacts for important economic sectors (e.g., the steel industry, the pulp and paper industry, the transportation industry, the farming industry, etc.) involved in the food and beverage packaging value chain. LCA studies are then assessed against the relevance matrix. Studies are said to comply with the matrix if their results include impact categories designated as “relevant” by the matrix given the relevant economic sectors covered by the studies. Conclusions from studies that do not evaluate key impact categories for those materials are noted as potentially less robust than conclusions from studies that include all key impact categories given their material options. For instance, conclusions from a high-quality GHG footprint analysis may nonetheless be deemed less robust than conclusions from a similar study that includes smog formation and energy demand results *for the purposes of this study* because the former only evaluates climate change impact, where smog formation and energy demand are considered material indicators. A credible comparison of alternative packaging designs manufactured from different materials should include evaluation and reporting of multiple and relevant inventory flows and

Figure C-2: Indication of relevance (not scale of impact) of certain environmental issues to major industry sectors associated with packaging based on available life cycle inventory data and assessment studies in the food and beverage sector [25,30, 33, 34, 35, 41, 42, 45, 49] from developed economies.

Relevance of Environmental Issues

	Climate Change	Eutrophication	Acidification	Ecotoxicity	Photochemical Oxidant Formation	Land Use	Water Use	Primary Energy Demand, Non-renewable
Forestry	0	0	+	0	+	0	+	0
Agriculture	++	++	++	++	++	++	++	++
Paper and Pulp	+	0	0	0	+	0	0	++
Aluminum	++	0	0	+	0	0	+	++
Steel	++	0	0	0	0	0	+	++
Glass Industry	+	0	0	0	0	0	0	+
Plastics Industry	+	0	0	0	+	0	0	+
Food Processing Industry	0	+	+	0	0	0	+	0
Transport Industry	+	0	0	0	+	0	0	+
Waste Management	+	0	0	+	0	0	0	0
	0	0	+	0	+	0	+	0
Use (Depends on Consumer Behavior)	++	++	++	++	++	++	++	++

Importance of sectors regarding listed environmental impacts

++	Very Relevant
+	Moderately Relevant
0	Little or no relevance

This relevance matrix refers to packaging of food products whereby the life cycle from cradle-to-table including end of life treatment of packaging is considered. The different environmental issues (columns) must not be compared. In addition, this table is not suitable to compare one material or issue to others, i.e. the rows must not be compared as well.

impact categories in order to adequately support knowledge mining outcomes.

The intent of the relevance matrix is therefore to establish the credibility of the knowledge mined based on the completeness of environmental impacts evaluated in the LCA and to document which studies best incorporate the elements deemed most useful for knowledge mining. It is not a final outcome of the knowledge mining exercise but rather part of a larger assessment on study quality. Study compliance with the relevance matrix is noted in the attribute matrix (discussed in Section C.2.1.2) and is used in conjunction with an assessment on study transparency, study assumptions, and whether or not the study has undergone critical review (per the ISO standards) in order to evaluate study quality.

Identifying the relevant impact categories can be done in multiple ways. For instance, prior experience and judgment could be used to choose impact categories, although choices will subsequently have to be justified since a practitioner's intuition may not always be correct. Another approach to defining a relevance matrix is to rely on established life cycle inventories. In the example shown in Figure C-2, life cycle inventories of several food life cycles including packaging were available. The qualitative matrix is based on the assessment of most of these data with different life cycle impact indicators and accounts for all life cycle stages, from cradle-to-table as well as the end-of-life treatment of packaging.

Alternatively, a less qualitative approach can be adopted such as the use of environmentally extended input-output tables (input-output LCA or EIO),[34,35,36] which quantify the environmental impacts of different economic sectors per dollar spent. A relevance matrix can be established based on these tables. The matrix represents dollars spent causing specific environmental impacts in an economic sector (where an economic sector is defined as a particular industry such as transportation or agriculture). Sector contribution to a particular impact category (such as climate change) is normalized to identify which sectors spend the most—and thereby are likely to be associated with the highest potential damage in that impact category. A variation of this approach was used by this study's knowledge mining exercise (Figure C-3).

Ultimately, the goal of a relevance matrix is to help the knowledge miner identify environmental hotspots in the life cycle of a product group related to economic sectors and thus help estimate the completeness of the studies investigated with regard to the environmental impacts covered. It is established once and its content helps to consistently complete the columns on life cycle impact assessment of the attribute matrix (see Section C.2.1.2). It is not a finalized study outcome and does not itself inform the outcomes of the knowledge mining exercise. In knowledge mining exercises that focus on topics outside LCA—for example, the role of packaging and infrastructure developments in mitigating global food loss—a relevance matrix may be unnecessary. However, in such a case the attribute matrix, discussed in the following section, would need additional elements, for example, "quantified evidence (field experiments and data) regarding the correlation of food loss and the role of packaging and infrastructure developments".

C.2.1.2 Attribute Matrix

All LCA studies analyzed need to be systematically documented to ensure traceability and manage the effort. For this purpose an attribute matrix is used. Important characteristics of the LCA studies such as commissioner, critical review, transparency, credits for recycling or energy recovery, and environmental impact category indicators covered are noted in the matrix. Work is facilitated by

34 European Commission, "Overall mapping of physical flows and stocks of resources to forecast waste quantities in Europe and identify life-cycle environmental stakes of waste prevention and recycling," *FORWAST* Available: http://forwast.brgm.fr/Index.asp.

35 N. Jungbluth, M. Stucki, M. Leuenberger, and C. Nathani, *Environmental impacts of Swiss consumption and production: a combination of input-output analysis with life cycle assessment,* Bern: Federal Office for the Environment, 2011.

36 S. Suh, "CEDA 4.0 User's Guide," 2010.

using pre-defined keywords. For example, in case of “allocation” pre-formulated keywords are for instance: cut-off, avoided burden, other, unknown, and N/A. This helps to sort the studies investigated according to, for instance, one particular allocation approach or one particular goal such as comparing packaging options. A list of aspects covered in the attribute matrix used in this study is detailed in Appendix D with a screenshot of the matrix developed for this study in Figure C4. In general, an attribute matrix should include not only study information (i.e., title, author, source, publication date, geographic scope, etc.) and LCA details, but also key points extracted from the study and whether it contributes to answering research questions. In general, attribute matrices will have to be developed and tailored to the specifics of a knowledge mining exercise.

C.2.1.3 Preliminary Investigation Outcomes

The preliminary investigation ends with the following outcomes. The knowledge miners know:

- The life cycle impact assessment categories that are relevant to the product group under analysis,
- The type of life cycle assessment studies they have to look for (e.g. only LCA (no material flow analysis), only comparisons of packaging options, etc.),
- The information they need to extract from the studies to complete the attribute matrix.

The preliminary investigation assures the traceability and completeness of the knowledge mining exercise. It prepares and facilitates the main investigation phase that follows.

C.2.2 Main Investigation

The main investigation starts with researching suitable LCA (or other relevant) studies covering the topic of interest. In this particular case, food and beverage packaging LCA studies were selected and a cursory review conducted to identify studies that show potential to provide answers to the research questions defined during the preliminary investigation. In a second step the studies investigated are documented within the attribute matrix.

The life cycle impact category indicators in the selected studies are listed and checked against the indicators considered important according to the relevance matrix. In the case of packaged food and beverage products, the relevance matrix (Figure C-3) shows that agricultural processes are of primary importance with regard to most indicators. Thus, in this case it is important that selected studies consider all these impacts if agricultural stages are included in the product system. Furthermore, the matrix shows that most sectors contribute to climate change impacts whereby acidification or land use are mostly dominated by one or two sectors only. If for instance the study includes products relying on the paper and pulp industry, water consumption should be included in the LCA study. The list of environmental impacts addressed by the study is compared to the list of required impacts according to the relevance matrix. The result of this comparison is documented in the attribute matrix as a degree of compliance with the relevance matrix.

In a third step the studies are evaluated regarding their fulfillment of minimum quality criteria, which allows them to be used in the further knowledge mining process. Quality criteria are (including examples of properties):

- Environmental impacts: The study should address all environmental impacts identified relevant for the product group under analysis.
- Critical review: Public comparative LCAs that claim ISO 14040 compliance must include the critical review report.
- Transparency: Documentation needs to be transparent to be able to make a qualified review of the study.

Studies that are deemed to be of lower quality should at least be noted either in the attribute matrix or when compiling the learnings. They may also be excluded from the further knowledge mining steps if this is considered to be an appropriate measure.

Finally the studies (either all or the ones of sufficient quality) are examined in view of statements related to the research questions formulated during the preliminary investigation and draft learnings are derived from these statements. After completing the analysis of the individual LCA studies, the statements and learnings based on the individual studies are grouped and synthesized.

C.2.3 Synthesis

Knowledge mining helps the decision maker to benefit from previously published life cycle assessment work about similar topics. A systematic review of high quality life cycle assessment reports and papers helps to improve understanding of the product system under study and to focus on previously identified environmental hot spots and important product system characteristics.

Drawing general learnings is the final and key outcome of the knowledge mining exercise. At the same time it is the crucial step because the large body of multifaceted information is condensed into a few, preferably clear, concise, and explicit statements. There is no prescriptive process for consolidating the knowledge amassed in the main investigation into a set of concise statements—which is why it is important the reviewer have some level of expertise with the topic. It becomes the reviewer's responsibility to understand and interpret the information and to identify aspects that are important from those considered inconsequential. This extraction of learnings may be facilitated by drafting a preliminary list of all key findings from the studies to determine frequency of messages, but ultimately it relies on the reviewer's judgment and interpretation of the information.

For example, key points from individual studies may only be true within their specific goal and scope. Hence, it may be difficult to formulate a general finding, and the conditions under which the finding is valid need to be specified. Thus learnings developed from these studies should include a statement about their validity.

The learnings from individual studies covering the same or a very similar goal and scope may contradict each other. In such cases one may first try to group the studies to find patterns within which the studies' findings are consistent. If this grouping is not successful, the learning should reflect the contentious outcomes of the studies analyzed.

Finally, an assessment concerning the study quality and reliability of the results of the knowledge mining study should be added. This assessment should in particular address possible publication biases and possible "file drawer" effects. The publication bias is a bias to what is published and what would be available for publication (but is not published). The file drawer effect occurs when studies are carried out in a research field without being published because their results may contradict with the outcome of published studies.

C.3 Application to Food and Beverage Packaging LCAs

Research question definition is the first step in the methodology in Section C.2. As such, questions concerning the value of life cycle thinking in food and beverage packaging were identified for this study's knowledge mining exercise. These questions included:

- Why adopt a life cycle approach in food and beverage packaging?
- Why assess the full life cycle when evaluating food and beverage packaging systems?
- Why evaluate multiple life cycle impact categories?
- Why include food and/or beverage in the packaging life cycle analysis?
- What is the intersection of the waste management hierarchy and LCA results?

Figure C-3: Indication of relevance (not scale of impact) of environmental impacts to certain sectors associated with food and beverage packaging based on environmentally extended input-output tables based on US data from CEDA.

Relevance of Environmental Issues

	Climate Change	Eutrophication	Acidification	Ecotoxicity	Photochemical Oxidant Formation	Land Use	Water Use	Primary Energy Demand, Non-renewable
Forestry	0	0	0	0	0	++	0	0
Agriculture	++	++	++	++	+	++	++	++
Paper and Pulp	+	+	0	0	+	+	++	+
Aluminum	++	+	0	+	+	0	+	+
Steel	++	+	0	+	0	0	+	+
Glass Industry	++	+	++	0	+	0	+	++
Plastics Industry	++	+	0	0	+	0	+	++
Food Processing Industry	+	+	0	0	0	0	++	+
Transport Industry	++	0	0	0	+	0	0	+
Waste Management	+	0	0	+	0	0	0	0
	0	0	+	0	+	0	+	0
Use (Depends on Consumer Behavior)	++	++	++	++	++	++	++	++

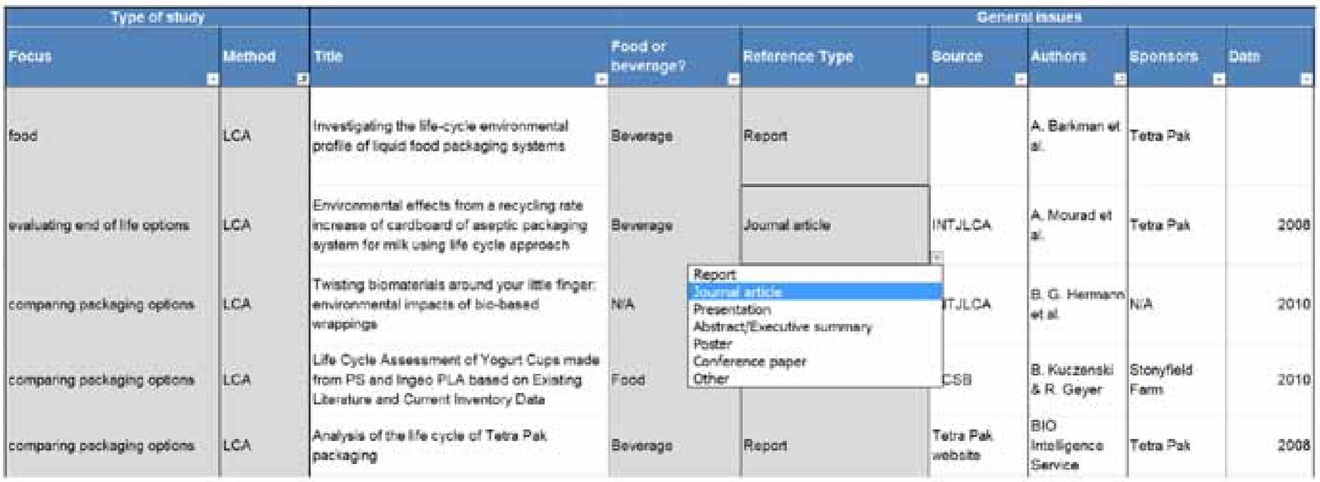
Importance of sectors regarding listed environmental impacts

++	Very Relevant
+	Moderately Relevant
0	Little or no relevance

This relevance matrix refers to packaging of food and beverage products whereby the life cycle from cradle-to-table including end of life treatment of packaging is considered. The different environmental issues (columns) must not be compared. In addition, this table is not suitable to compare one material or issue to others, i.e. the rows must not be compared as well.

Sources:
1) S. Suh, "CEDA 4.0 User's Guide," 2010.
2) http://www.cedainformation.net/home.asp

Figure C-4: Screenshot of a portion of the attribute matrix



Type of study		General issues						
Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date
food	LCA	Investigating the life-cycle environmental profile of liquid food packaging systems	Beverage	Report		A. Barkman et al.	Tetra Pak	
evaluating end of life options	LCA	Environmental effects from a recycling rate increase of cardboard of aseptic packaging system for milk using life cycle approach	Beverage	Journal article	INTJLCA	A. Mourad et al.	Tetra Pak	2008
comparing packaging options	LCA	Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings	N/A	[illegible]	TJLCA	B. G. Hermann et al.	N/A	2010
comparing packaging options	LCA	Life Cycle Assessment of Yogurt Cups made from PS and Ingeo PLA based on Existing Literature and Current Inventory Data	Food	[illegible]	CSB	B. Kuczenski & R. Geyer	Stonyfield Farm	2010
comparing packaging options	LCA	Analysis of the life cycle of Tetra Pak packaging	Beverage	Report	Tetra Pak website	BIO Intelligence Service	Tetra Pak	2008

Once the questions were identified, a relevance matrix (Figure C-3) was defined. The matrix for this study was based on environmentally extended input-output tables using US data from Suh30 and CEDA (Comprehensive Environmental Data Archive)37 (although as Section C.2.1.1 indicates, there are other approaches to define a relevance matrix). Suh shows the environmental impacts per dollar spent for multiple economic sectors. These impacts are multiplied with the dollars spent in the involved economic sectors to get the relative importance of each sector with respect to environmental impacts. Environmentally extended input-output tables, rather than existing LCA studies, were chosen so that the relevance matrix was generated using independent data rather than the same LCA studies covered during the knowledge mining exercise. The matrix was used as shorthand to evaluate the quality and relevance of evaluated studies.

For this analysis, sectors that account for 10% or higher of total amount spent in a particular impact category are assigned a red "++", sectors that represent between 1% to 10% of spending were assigned a peach "+", and the remaining sectors a blue "0". The resulting matrix in Figure C-3 provides a directional indication of the relative importance of sectors within each impact category. Given the degree of uncertainty in input-output analysis, it should be emphasized that the relevance matrix is simply a means to assessing LCA quality: it does not represent a finalized outcome of this study, nor is it used to actually derive learnings or to encourage the use of input-output LCA in packaging analyses.

Then an attribute matrix (a screenshot of which is shown in Figure C-4) was created as a means to systematically document studies reviewed during knowledge mining. The matrix's purpose was not only to facilitate study traceability, but also to help sort studies, filter out those deemed of lower quality or applicability to the research questions, and to draw out key concepts and learnings. Thus, attributes included in matrix represented study characteristics that were important to understanding the basics of the study (e.g., was it an LCA on packaging only or did it include both food and packaging), LCA assumptions (e.g., geographic scope, impact categories, and system boundaries), study quality (e.g., transparency of input assumptions), and meta-data (e.g., author and reference type). Along with these attributes, key conclusions from each study were noted, as well as whether the study contributed to answering any of the research questions. Specifics of the attribute matrix developed for this study are presented in Appendix D.

37 http://www.cedainformation.net/home.asp

Once both matrices were defined, collected LCAs and other literature were used to populate the attribute matrix. Expert judgment was exercised to assess whether study conclusions were reasonable given assumptions presented in the paper. If so, key conclusions were noted in the attribute matrix so that they could later be used to develop learnings. Next, matrix contents, in particular study conclusions and which studies contributed to each research question, were reviewed and used to identify important points based on study results. These key points formed the basis for learnings that are detailed in Section 5 of this report.

Throughout the process, multiple groups of participants contributed to this study (see the Acknowledgements section for a list of participants). The core team conducted the research, knowledge mining and resulting analysis for the project, as well as coordinated project meetings and administrative aspects. Decisions regarding analysis were made by the core team with input from other participants. These participants included *sponsors*, who provided financial resources, served as technical resources on packaging and food questions, and provided literature as part of knowledge mining, as well as *stakeholders*, who were identified by the sponsors and core team and provided their perspective on the food and beverage packaging industry through interviews conducted by core team members. These interviews were used to aid identification of LCA research for inclusion in the knowledge mining exercise, as well as to improve understanding of the broader scope of issues surrounding packaging system performance —environmental and otherwise—that were not gleaned from the knowledge mining exercise due to its restricted focus on LCA-related literature. Both sponsors and stakeholders were relied on to ensure a holistic perspective on research questions, though the knowledge mining exercise was limited to extracting insights from LCAs specifically. A draft version of this report was first provided to sponsors; once their feedback was incorporated, stakeholders and the Technical Review Committee—the latter on behalf of the International Life Cycle Board—reviewed this report for technical quality assurance prior to final publishing.

Based on a broad consultation from sponsors and stakeholders, food and beverage packaging LCAs (and other studies) were identified and used to populate the attribute matrix. While the goal is not to develop a comprehensive literature review, efforts were made to ensure a representative set of literature and to identify gaps that future analyses could potentially fill. Key points and conclusions from each of the studies were entered into the attribute matrix, along with research questions each study contributed to.

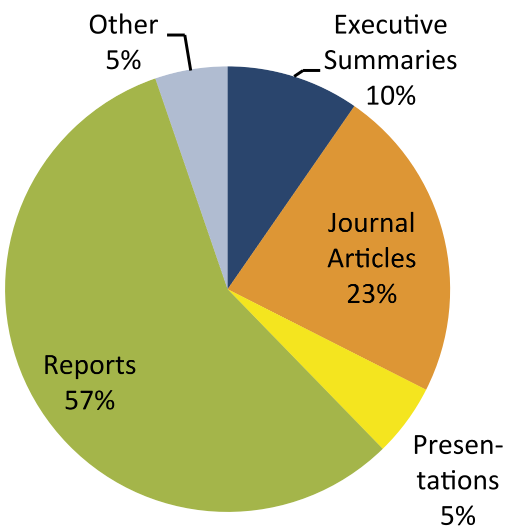
Since the goal of this exercise was to ultimately consolidate knowledge from existing studies, expert judgment was needed to assess validity of key points and conclusions, given study assumptions, and to summarize those points in a set of learnings. These learnings are detailed in Section 5 and the studies reviewed are outlined in Section C.3.1.

C.3.1 Overview of Studies Reviewed

The literature search conducted on food and beverage packaging relied on a combination of on-line research as well as input from this study's sponsors and stakeholders. Only publically available studies were considered. The majority of reviewed studies were published in English, but attempts were made to include studies published in other languages.

Over 110 studies were entered into the attribute matrix. These studies included not only food and beverage packaging LCAs, but also food and beverage product LCAs that included packaging within system boundaries, literature addressing food and food waste, and papers on environmental impacts of packaging and waste management. Figure C5 shows a breakdown of document type of studies.

Figure C5: Breakdown of document type included in attribute matrix



Of the 110 studies in the attribute matrix, 69 of these represented the life cycle assessment and life cycle inventory studies that formed the primary basis for the learnings. Studies specifically cited in the text are listed in Section C.3.3. Of these studies:

- 23 were focused on food and/or food packaging, 23 on beverage and/or beverage packaging, and the remainder addressed packaging materials or applications that could be either for food or beverages;
- 37 were conducted in order to compare alternative packaging designs; 20 were focused on food or beverage products, but included packaging in the analysis in order to understand the relevance of packaging in the product assessment; and the remainder addressed end-of-life scenarios or LCA methodology;
- 58 considered cradle-to-grave impact of the packaging and/or cradle-to-table impact of the food;
- All except one were published in 1999 or later (the one exception was published in 1990), with 55 studies published in 2006 or afterwards;
- The majority were conducted for packaging in Western Europe or the United States; two addressed packaging in Singapore, two evaluated food and packaging waste in Australia, two focused on emerging economies—Brazil and Mexico;
- Around a third of the studies were critically reviewed according to ISO 14040/14044 guidelines; others did not specify whether or not a review took place, although it should be noted some of these were published in peer reviewed journals;
- Materials assessed in the various studies included glass, paperboard, steel, aluminum, plastics (HDPE, LDPE, LLDPE, PC, PET, PLA, PP, PS, PVC), and composites thereof;
- Impact categories evaluated included energy demand, water use, land use, acidification, eutrophication, climate change (a.k.a. global warming), smog formation, ozone creation, toxicity.

Generated learnings provided the foundation for guidance in the application of life cycle thinking to food and beverage packaging systems. Not all studies included in the attribute matrix were instrumental in generating learnings since not all addressed life cycle assessment or life cycle thinking. Non-LCA studies, along with stakeholder interviews, were used to provide guidance on the broader scope of issues related to the environmental impacts of packaging. While the knowledge mining exercise was limited in scope to extracting knowledge from published LCAs, these insights guided the core team in evaluating what issues LCA is or is not able to address.

C.3.1.1 Limitations

The primary objective of this study was to use knowledge mining to articulate the value of LCA in food and beverage packaging applications. Originally, the hope was to develop region-specific learnings targeted at both developed and developing economies. Due to the limited number of studies focused on developing economies available to the core team, however, learnings are presented only for developed economies.

This is not to say that conclusions are irrelevant for developing economies: there was simply not enough information to draw specific conclusions for these regions. It is unclear whether this report's lack of LCAs representative of developing economies is due to the lack of representative data, the publication of these studies in the country's native language (i.e., not English), simply an indication of where LCA resources are available, or some other reason[38]. For instance, in the case of Brazil, representative data exist, but are in Portuguese and not publically available. On one hand non-LCA studies indicate the important role packaging has to play in food distribution in emerging economies (e.g., [57–59]), but do not necessarily demonstrate the value of applying life cycle assessment. On the other hand non-LCA studies also show that the share of food lost is much higher in developed countries with sophisticated packaging systems as compared to poor countries, where packaging is much less in use[39]. CETEA (Centro de Tecnologia de Embalagem), however, is working to address the lack of life cycle inventory data—at least from a Brazilian perspective—and the Swiss government has started the Sustainable Recycling Industries initiative to spread LCA to developing economies.

Additionally, there is an increasing but yet small number of packaging LCAs that accounted for food or beverage loss or content. The majority implicitly assumed that loss rates were the same for all alternative packaging designs. While this assumption does not detract from the value of conducting an LCA, it can potentially change the conclusions of an individual analysis. New research will have to be conducted to address this, however, as it is not feasible to assess how LCA results from reviewed literature might have been different had food loss been considered.

38 For example, other studies may exist, but are possibly limited to a business' internal audience and thus unpublished, or perhaps published in "gray literature" that may not have been accessible or even known by the sponsoring organizations.

39 W. Moomaw., T. Griffin, K. Kurczak, and J. Lomax, *The Critical Role of Global Food Consumption Patterns in Achieving Sustainable Food Systems and Food for All, A UNEP Discussion Paper*, United Nations Environment Programme, Division of Technology, Industry and Economics, Paris, France, 2012.

Learnings in Section 5.1.3 are based on the studies that do consider food and beverage loss or content as well as the observation that if packaging is a minor contributor to a food or beverage product's overall life cycle impact, it stands to reason that the impact associated with product losses can potentially exceed that associated with just the packaging. Thus, the packaging design that minimizes losses (evidenced by field measurements) minimizes environmental burdens.

C.3.2 Data Quality

Since the goal is to mine knowledge rather than data, the standard LCA methodology of assessing data quality through precision, completeness, consistency, reproducibility, and representativeness is not necessarily applicable to the study as a whole. In order to ensure supportable learnings, one needs to assess not only whether the study uses high-quality data, but also whether the study itself follows the LCA methodology, makes representative assumptions given the product system being evaluated, and interprets results in light of these assumptions and the goal and scope defined within the LCA study. LCA studies deemed of higher quality were selected to support the learnings (presented in Section 5). Study quality was assessed based not only on the study's compliance with the relevance matrix, but also on whether the study was critically reviewed, presented information on some key LCA elements (e.g., functional unit, system boundary, open-loop allocation approach, etc.), obtained background data from respected sources, and presented inputs and outputs transparently. Previous LCA experience was leveraged in order to determine whether study results were reasonable and did indeed reflect assumptions. Of the 69 LCA studies, 52 are explicitly referenced in support of the learnings; the remainder were used in limited fashion given inappropriate study assumptions or lack of transparency.

C.3.3 Knowledge Mining References

The list below represents LCA studies that are explicitly cited in this report. The remaining LCA studies that were not cited, along with non-LCA studies reviewed during knowledge mining, can be found in the attribute matrix in Appendix D.

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Appendix D: Attribute Matrix

The list below includes main topics, subtopics and pre-formulated keywords of the attribute matrix developed for mining LCAs of food and beverage packaging:

Type of study:

- *Focus*: general packaging, food, relevance of packaging in product life cycle, comparing packaging options, evaluating end of life options, waste, meta-analysis, other
- *Method*: LCA, LCI, material flow analysis (MFA), other, N/A

General issues:

- *Title*
- *Food or beverage*: food, beverage, both, other, N/A
- *Reference type*: report, journal article, presentation, abstract/executive summary, poster, conference paper, other
- *Source*
- *Authors*
- *Sponsors*
- *Date*
- *Geographic scope*
- *Peer reviewed*: yes review available, yes but review not available, no
- *Packaging material*
- *Background data*

LCIA:

- *Impact categories*
- *Compliance with relevance matrix*: yes, no, partially, mostly, unknown, N/A

Methodology:

- *Input transparency*: fully transparent, lack of qualitative input transparency[40], lack of quantitative input transparency[41], N/A
- *Output transparency*: fully transparent, lack of quantitative output transparency[42], N/A
- *Type*: attributional process-based LCA, consequential process-based LCA, input-output LCA, Hybrid (combination of process-based and input/output), unknown, N/A
- *Functional unit*
- *Allocation*: cut-off, avoided burden, other, unknown, N/A
- *Credits recycling*: 100% to the product which generates recycled content, 100% to the product which uses the recycled content, 50%/50% to both products, other, unknown, N/A
- *System boundaries*: cradle-to-grave, cradle-to-table, cradle-to-gate, gate-to-gate, gate-to-grave, other, unknown, N/A
- *Food losses considered*: yes assumption, yes empirical data, no, unknown, N/A
- *Includes uncertainty assessment*: yes sensitivity analysis, yes statistic methods, yes sensitivity & statistic methods, yes qualitative, no ,unknown
- *Secondary and/or tertiary packaging included*: yes, no, unknown, N/A

Research questions:

- *Value & relevance of LC approach*
- *Value & relevance of including all LC stages*
- *Value & relevance of including multiple LCI flows / impact categories*
- *Value & relevance of including food / beverage*
- *Characteristics of future LCAs that should be considered*
- *Connection / contradiction with waste management hierarchy*

Additional information:

- *Next steps*
- *Is further review recommended?*
- *Preliminary learnings*
- *Notes*

40 System boundaries not documented, see L. Price and A. Kendall, "Wind Power as a Case Study: Improving Life Cycle Assessment Reporting to Better Enable Meta-analyses," *Journal of Industrial Ecology*, vol. 16, Apr. 2012, pp. S22–S27.

41 Actual inputs to the system are not reported or with insufficient detail, see reference in footnote 34

42 Granularity of reporting, e.g. GHG emissions are only shown over full life cycle, see reference in footnote 34

Table D1: Attribute matrix of LCA studies reviewed—general issues and methodology

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
1	Food	LCA	Case Studies Life Cycle Assessment of a Basic Lager Beer	Beverage	Journal article	INTJLCA	S. Talve	unknown	2001	EU	no	glass	KCL-ECO
2	relevance of packaging in product life cycle	LCA	Coffee: family and portion pack showing the relative importance on environmental impact of different consumer habits relating to coffee preparation and consumption.	Beverage	Abstract / Executive summary	EAFA website	esu-services	FPE (Flexible Packaging Europe)	2008	EU	no	Al foil	not listed
3	comparing packaging options	LCA	Comparative LCA of 4 types of drinking cups used at events	Beverage	Report	OVAM website	VITO (Flemish Institute for Technological Research)	OVAM (Flemish Public Waste Agency)	2006	EU-15	yes, review available	PC, PP, PLA, PE-coated cardboard	PlasticsEurope NatureWorks VITO-LCA DB other literature
4	comparing packaging options	LCA	Comparative Life Cycle Assessment of beverage cartons cb3 and cb3 EcoPlus for UHT milk	Beverage	Report	IFEU	F. Wellenreuther et al.	SIG Combibloc	2010	EU	yes, review available	LPB, LDPE, Al, PA, PP, HDPE (carton + spout)	other literature
5	food	LCA	Comparative Life Cycle Assessment of Malt-based Beer and 100 per cent Barley Beer	Beverage	Report	Novozymes website	J. H. Kloverpris et al	Novozymes A/S, Harboes Bryggeri	2009	DK	yes, review available	none	ecoinvent, LCA Food
6	comparing packaging options	LCA	Analysis of the life cycle of Tetra Pak packaging	Beverage	Report	Tetra Pak website	BIO Intelligence Service	Tetra Pak	2008	FR	yes, review available	aseptic, plastic, glass, steel, stand-up pouch	ecoinvent, WISARD
7	evaluating end of life options	LCA	Environmental effects from a recycling rate increase of cardboard of aseptic packaging system for milk using life cycle approach	Beverage	Journal article	INTJLCA	A. Mourad et al.	Tetra Pak	2008	BZ	no	paper, PE, Al foil	other literature
8	relevance of packaging in product life cycle	LCA	Environmental impact of packaging and food losses in a life cycle perspective	Food	Abstract / Executive summary	J. Cleaner Pro	H. Williams & F. Wikstrom		2011	EU	no	not listed	not listed
9	comparing packaging options	LCA	Environmental impacts of conventional plastic and bio-based carrier bags: Part 1 - Life cycle production	N/A	Journal article	INTJLCA	H. H. Khoo et al.		2010	SG	no	PHA, PP	other literature
10	comparing packaging options	LCA	Environmental impacts of conventional plastic and bio-based carrier bags: Part 2 - EoL	N/A	Journal article	INTJLCA	H. H. Khoo et al.		2010	SG	no	PHA, PP	other literature
11	comparing packaging options	LCA	Environmental impacts of packaging and packaged food - Role of packaging	Food	Conference paper	13th TAPPI European PLACE Conf.	J.-M. Katajajuuri et al.	MTT and Lappeenrantra Institute	2011	FI	no	Laminate, plastic, corrugate	other literature
12	evaluating end of life options	LCA	Environmental implications and market analysis of soft drink packaging systems in Mexico. A waste management approach	Beverage	Journal article	INTJLCA	O. Romero-Hernandez et al.	APREPET	2009	MX	no	PET, Al, glass	other literature
13	food	LCA	Environmental Life Cycle Assessment (LCA) Case Studies for Western Australian Grain Products	Food	Report		V. Narayanaswamy et al.	GRDC (Grains R&D Corp.)	2004	AU	yes, review not available	Glass, Al, LDPE, HDPE, PET	other literature

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transpar-ency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
GWP, AP, EP, oxygen depletion, POCP	yes	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	10 hL beer (505 multi-packs of bottled beer)	unknown	N/A	cradle-to-gate	no	no	yes
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	to prepare one cup of coffee ready to drink at home	unknown	unknown	cradle-to-table	yes, assumption	yes, sensitivity analysis	no
EI99 (AP, EP, CC, etc.)	partially	fully transparent	fully transparent	process-based LCA, attributional	the recipients needed for serving 100 liter beer or soft drinks on a small-scale indoor (2000-5000 visitors) and a large-scale outdoor event (>30 000 visitors)	avoided burden	100% to the product which generates recyclate	cradle-to-grave	N/A	yes, sensitivity analysis	no
GWP, AP, EP, POCP, toxicity, PED	yes	fully transparent	lack of quantitative output transparency	process-based LCA, attributional	packaging and delivery to the point of sale of 1000 L UHT milk	cut-off	100% to the product which uses the recyclate	cradle-to-grave	no	yes, sensitivity analysis	yes
GWP, AP, EP, POCP, CED, land use	partially	fully transparent	fully transparent	process-based LCA, consequential	7 tons of extract after boiling	unknown	N/A	cradle-to-gate	no	yes, sensitivity analysis	no
GWP, PED, AP, EP, POCP, ADP, toxicity	mostly	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	Depends on packaged food (1L milk, 1L juice, 250mL juice, 400mL food)	avoided burden	100% to the product which generates recyclate	cradle-to-grave	no	yes, sensitivity analysis	yes
LCI: energy, resource consumption, air & water emissions	partially	fully transparent	lack of quantitative output transparency	process-based LCA, attributional	1,000 liters of milk, distributed in corrugated paperboard trays with 12 x 1 L units, wrapped with polyethylene shrink film, arranged on one-way wooden pallets	avoided burden	100% to the product which generates recyclate	cradle-to-grave	no	no	yes
not listed	unknown	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	not listed	unknown	unknown	cradle-to-table	yes, assumption	unknown	N/A
GWP, AP, POCP	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	one "standard bag" with carrying capacity of 20 kg	N/A	N/A	cradle-to-gate	no	yes, sensitivity analysis	no
GWP, AP, POCP	partially	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	one "standard bag" with carrying capacity of 20 kg	avoided burden	N/A	cradle-to-grave	no	yes, sensitivity analysis	no
AP, EP, GWP	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1,000 kg of each product consumed	unknown	unknown	cradle-to-table	yes, empirical data	yes, sensitivity analysis	yes
waste, GWP	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	???	avoided burden	unknown	cradle-to-grave	no	yes, sensitivity analysis	no
energy, GWP, EP, AP, human tox, ecotox	mostly	fully transparent	lack of quantitative output transparency	process-based LCA, attributional	Varies based on product	cut-off	100% to the product which uses the recyclate	cradle-to-table	no	no	no

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
14	comparing packaging options	LCA	Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking & Assessment: A Sustainable Materials Management Demonstration Project	Food	Report		M. Stevenson et al.	US EPA	2010	US	no	Corrugate, PET, PS	ecoinvent, US LCI DB
15	food	LCA	Investigating the life-cycle environmental profile of liquid food packaging systems	Beverage	Report		A. Barkman et al.	Tetra Pak		EU	no	aseptic laminate (board, LDPE, Al)	other literature
16	relevance of packaging in product life cycle	LCA	LCA of a Roast Stored in Aluminium Household Foil	Food	Abstract / Executive summary	EAFA website	esu-services	EAFA	2008	EU	no	Al foil	not listed
17	comparing packaging options	LCA	LCA of an Italian lager beer	Beverage	Journal article	INTJLCA	M. Cordella et al.	N/A	2008	IT	no	glass, steel	ecoinvent
18	relevance of packaging in product life cycle	LCA	LCA of Chocolate Packed in Aluminium Foil Based Packaging	Food	Abstract / Executive summary	EAFA website	esu-services	GDA and EAFA	2009	EU	no	Al foil, paper	not listed
19	relevance of packaging in product life cycle	LCA	LCA of Packed Food Products - the function of flexible packaging - Case Study: Butter	Food	Abstract / Executive summary	EAFA website	esu-services	FPE (Flexible Packaging Europe)	2008	EU	no	Al foil, synthetic wax, paper	not listed
20	relevance of packaging in product life cycle	LCA	LCA of packed food products: Deep-frozen spinach	Food	Abstract / Executive summary	EAFA website	esu-services	FPE (Flexible Packaging Europe)	2008	EU	no	LLDPE	not listed
21	relevance of packaging in product life cycle	LCA	LCA of Ready-to-Serve Goulash Soup Packed in Stand-Up Pouches	Food	Abstract / Executive summary	EAFA website	esu-services	EAFA	2011	EU	no	plastic laminate, aluminum foil	not listed
22	relevance of packaging in product life cycle	LCA	LCA of Ready-to-Serve Lasagne Bolognese Packed in Aluminium Foil Containers	Food	Abstract / Executive summary	EAFA website	esu-services	EAFA	2009	EU	no	Al foil	not listed
23	comparing packaging options	LCA	LCA of Yoghurt Packed in Polystyrene Cup and Aluminium-Based Lidding	Food	Abstract / Executive summary	EAFA website	esu-services	GDA and EAFA	2009	EU	no	Al foil, PS	not listed
24	food	LCA	Life cycle analysis of bread production – a comparison of eight different options	Food	Presentation	LCA in the Agri-food sector conference	G. A. Reinhardt	IFEU	2003	DE	no	N/A	not listed
25	food	LCA	Life cycle assessment of bread produced on different scales	Food	Journal article	INTJLCA	K. Andersson & T. Ohlsson	Swedish Waste Research Council	1999	SE	no	not specified	not listed
26	comparing packaging options	LCA	Life cycle assessment of consumer packaging for liquid food	Beverage	Presentation		E. Eriksson et al.	Tetra Pak	2009	DK	yes, review not available	aseptic, liquid carton board, PET, HDPE, glass	other literature
27	comparing packaging options	LCA	Life cycle assessment of different reuse percentages for glass beer bottles	Beverage	Journal article	INTJLCA	T. Mata & C. Costa		2001	PT	no	glass	BUWAL
28	food	LCA	Life cycle assessment of drinking Darjeeling tea	Beverage	Report	ESU Services website	esu-services		2010	EU	no	not specified	not listed

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transpar-ency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
GWP, AP, POCP, EP, respiratory, water	partially	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	1) One hundred pounds (100 lbs) of tomatoes delivered to supermarket 2) One hundred pounds (100 lbs) of tomatoes delivered to consumer for consumption	unknown	unknown	cradle-to-table	yes, empirical data	yes, sensitivity analysis	yes
energy, GWP, AP, EP, POCP, resources, waste	mostly	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	100 litres of food product delivered to the consumers in 1-litre packages	avoided burden	100% to the product which generates recyclate	cradle-to-grave	yes, empirical data	no	no
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the preparation of 1 kg roast including half of the roast stored in aluminium household foil	unknown	unknown	cradle-to-table	no	no	no
Endpts: human health, eco-system quality, resources	no	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1 L of beer and the fraction of packaging allocated to such a litre (1/20 of a 20 L steel keg or three 33 cL glass bottles)	unknown	unknown	cradle-to-grave	yes, empirical data	yes, statistic methods	yes
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1 kg chocolate, packed in 100 gram chocolate bars to be consumed in the household	unknown	unknown	cradle-to-table	no	no	no
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the provision of one kilogram of butter ready to eat at home	unknown	unknown	cradle-to-table	yes, assumption	yes, sensitivity analysis	no
CED, GWP, ODP, AP, EP	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the preparation of one kilogram of spinach ready to eat at home	unknown	unknown	cradle-to-table	no	yes, sensitivity analysis	no
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the preparation of 1 package containing 570 ml goulash soup packed in stand-up pouch ready to consume at the household	unknown	unknown	cradle-to-table	no	no	no
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the preparation of 1 kg ready-to-serve lasagne Bolognese ready to consume in single portions of 400g or 1000g	unknown	unknown	cradle-to-table	no	no	no
CED, GWP, ODP, AP, EP	partially	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1 kg yogurt	cut-off	100% to the product which uses the recyclate	cradle-to-grave	yes, assumption	yes, sensitivity analysis	no
ADP, GWP, ODP, AP, EP, POCP, land	mostly	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1 kg of bread for consumption at home	unknown	unknown	cradle-to-table	no	yes, sensitivity analysis	no
CED, GWP, AP, EP, POCP	partially	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1 kg of bread for consumption at home	avoided burden	N/A	cradle-to-table	no	yes, sensitivity analysis	no
GWP, AP, EP, POCP, ODP	yes	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	Varies by product	avoided burden	100% to the product which uses the recyclate	cradle-to-grave	no	yes, sensitivity analysis	no
GWP, AP, EP, POCP, ODP, toxicity	yes	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	the delivery of 330 litres of beer to the consumer	avoided burden	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	yes
ecological scarcity, GWP, CED	unknown	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	preparation of one cup (250 ml) of tea ready to drink at home in Europe	unknown	unknown	cradle-to-table	no	no	yes

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
29	comparing packaging options	LCA	Life Cycle Assessment of Drinking Water Systems: Bottle Water, Tap Water, and Home/Office Delivery Water	Beverage	Report	OR DEQ website	Franklin Associates	Oregon Dept. Env. Quality	2009	US	yes, review not available	PET, PLA, glass	US LCI, Franklin's DB
30	food	LCA	Life Cycle assessment of frozen cod fillets including fishery-specific environmental impacts	Food	Journal article	INTJLCA	F. Ziegler et al		2003	UK	no	LDPE laminated cardboard, LDPE	CIT-Ekologic
31	comparing packaging options	LCA	Life cycle assessment of polylactic acid and polyethylene terephthalate bottles for drinking water	Beverage	Journal article	Env. Progress & Sus. Energy	F. Gironi et al.		2011	EU	no	PLA, PET	ecoinvent
32	comparing packaging options	LCA	Life Cycle Assessment of Supermarket Carrier bags	N/A	Report	Environment Agency website	C. Edwards & J. M. Fry	Environment Agency	2011	UK	yes, review available	HDPE, LDPE, PP, starch-polyester, cotton, paper	ecoinvent
33	comparing packaging options	LCA	Life Cycle Assessment of the Stonyfield Farm Product Delivery System	Food	Report	CSS, UMich	D. Brachfeld et al.	Stonyfield Farm Inc.	2001	US	no	HDPE, PLA, paperboard	other literature
34	comparing packaging options	LCA	Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots	Food	Journal article	INTJLCA	S. Humbert et al.	Nestle	2009	DE, ES, FR	yes, review not available	glass, plastic (steel, paper, cardboard)	ecoinvent
35	comparing packaging options	LCA	Life Cycle Assessment of Yogurt Cups made from PS and Ingeo PLA based on Existing Literature and Current Inventory Data	Food	Report	UCSB	B. Kuczenski & R. Geyer	Stonyfield Farm	2010	US, EU	no	PLA, PS	other literature
36	food	LCA	Product Category Rules (PCR) for preparing an Environmental Product Declaration (EPD) for Product Group: Wild caught fish	Food	Other	http://pcr-library.edf.org.tw/data/norway/NPCR07FishEN.pdf	Erwin Meissner Schau		2006	NO	no	none	N/A
37	comparing packaging options	LCA	Resource and Environmental Profile Analysis of Polyethylene and Unbleached Paper Grocery Sacks	N/A	Report		Franklin Associates	Santa Cruz County	1990	US	no	HDPE, LLDPE, paper	not listed
38	comparing packaging options	LCA	Resource and Environmental Profile Analysis of Polyethylene Milk Bottles and Polyethylene-coated Paperboard Milk Cartons	Beverage	Report		Franklin Associates	Monroe County		US	no	HDPE, LDPE, paperboard	not listed
39	comparing packaging options	LCA	Single Use Cups or Reusable (coffee) Drinking Systems: An Environmental Comparison	Beverage	Abstract / Executive summary		T.N. Ligthart, A.M.M. Ansems	TNO	2007	EU-15	no	porcelain, PS, paper, earthenware	not listed
40	other	LCA	Subjective Choices in Life Cycle Assessment: How many alternatives are enough?	N/A	Presentation	LCA XI	S. Hunter	Dow Chemical	2011	US	no	N/A	N/A

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transpar-ency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
AP, EP, GWP, ODP, SP, carcinogenic, non-carcinogenic, ecotox, respiratory effects, water use	yes	fully transparent	fully transparent	process-based LCA, attributional	1,000 gal drinking water delivered to consumers	cut-off	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	yes
GWP, AP, EP, POCP	partially	lack of quantitative input transparency	lack of quantitative output transparency	input-output LCA	1 consumer package (400 g) of frozen cod fillets	unknown	unknown	cradle-to-table	yes, empirical data	no	yes
AP, EP, GWP, PED, land, POCP, ODP, (non) carcinogens, respiratory, toxicity, etc.	yes	fully transparent	lack of quantitative output transparency	process-based LCA, attributional	1000 units of 500-mL bottles to be used for drinking water	avoided burden	100% to the product which uses the recyclate	cradle-to-grave	no	no	no
AP, EP, toxicity, POCP, RD, etc.	partially	fully transparent	fully transparent	process-based LCA, attributional	Carrying one month's shopping (483 items) from the supermarket to the home in the UK in 2006/07.	avoided burden	100% to the product which generates recyclate	cradle-to-grave	no	yes, sensitivity analysis	yes
energy, material, water, air emissions, water emissions, waste, GWP, ODP, max conc	yes	fully transparent	fully transparent	process-based LCA, attributional	1,000 lbs. of yogurt delivered to market	cut-off	100% to the product which uses the recyclate	cradle-to-grave	no	yes, sensitivity analysis	yes
AP, EP, GWP, PED, land, POCP, ODP, (non) carcinogens, respiratory, toxicity, etc.	yes	fully transparent	fully transparent	process-based LCA, attributional	provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007 (200-g packaging size)	avoided burden	100% to the product which generates recyclate	cradle-to-grave	no	yes, sensitivity & statistic methods	yes
energy, AP, EP, GHG emissions, GWP, toxicity, land, water	partially	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1 kg material	unknown	unknown	cradle-to-grave	no	no	no
emissions, GWP, ODP, AP, POCP, EP, ecotox	mostly	lack of qualitative input transparency	N/A	process-based LCA, attributional	1 kg fish delivered to consumer	unknown	unknown	cradle-to-table	unknown	unknown	no
PED, recycling, combustion, landfill	no	fully transparent	lack of quantitative output transparency	process-based LCA, attributional	10,000 equivalent uses of polyethylene (PE) and paper sacks	avoided burden	50%/50% to both products	cradle-to-grave	no	no	no
PED, emissions, waste, recycling, combustion	partially	fully transparent	fully transparent	process-based LCA, consequential	delivery of 1,000 gallons of milk	avoided burden	50%/50% to both products	cradle-to-grave	no	no	no
ADP, GWP, ODP, POCP, EP, AP. Toxicity	yes	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, consequential	The dispensing of 1,000 units of hot drinks (tea/coffee/hot chocolate) from a vending machine or dispenser in an office or factory environment.	unknown	unknown	cradle-to-grave	no	yes, sensitivity analysis	no
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	yes, qualitative	N/A

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
41	comparing packaging options	LCA	Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers	N/A	Journal article	ES&T	M. D. Tabone et al		2010	US	no	plastics	ecoinvent
42	relevance of packaging in product life cycle	LCA	The carbon footprint of bread	Food	Journal article	INTJLCA	N. Espinoza-Orias et al		2011	UK	no	polyethylene, paper	ecoinvent, other literature
43	food	LCA	The Carbon Footprint of Fat Tire Amber Ale	Beverage	Report		The Climate Conservancy	New Belgium Brewing Company	2008	BE	no	glass, paper, cardboard, steel, wood	other literature
44	relevance of packaging in product life cycle	LCA	The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe	N/A	Presentation	Denkstatt website		denkstatt	2011	EU	no	plastics vs. alternatives	not listed
45	relevance of packaging in product life cycle	LCA	The impact of plastics on life cycle energy consumption and GHG emissions in Europe	N/A	Report	Denkstatt website	H. Pilz et al.	Denkstatt, Plastics Europe	2010	EU	yes, review not available	plastics vs. alternatives	ecoinvent, PlasticsEurope
46	comparing packaging options	LCA	The life cycle emissions of wine imported to the UK	Beverage	Report	WFA website	Peter Lee	WRAP	2007	UK	no	glass bottles, steel tanks, polyethylene flexitank	other literature
47	relevance of packaging in product life cycle	LCA	The role of flexible packaging in the life cycle of coffee and butter	Both	Journal article	INTJLCA	esu-services	FPE (Flexible Packaging Europe)	2009	EU	no	Al laminate	ecoinvent v2.0
48	relevance of packaging in product life cycle	LCA	The sustainability of communicative packaging concepts in the food supply chain. A case study: part 1. Life cycle assessment	Food	Journal article	INTJLCA	Dobon	N/A	2011	NL	no	nanoclay-based PLA tray	other literature
49	comparing packaging options	LCA	The Sustainability of Packaging Systems for Fruit and Vegetable Transport in Europe based on Life-Cycle-Analysis – Update 2009	Food	Report		University of Stuttgart, PE International	Stiftung Initiative Mehrweg	2009	EU	yes, review available	wood, cardboard, plastic	GaBi
50	comparing packaging options	LCA	Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings	N/A	Journal article	INTJLCA	B. G. Hermann et al.	N/A	2010	EU	no	Laminates (paper, PE, PP, PLA, PET, Al, cellulose, EVA)	other literature
51	relevance of packaging in product life cycle	LCA	Wine: effect of different closure systems on wine loss due to tainting and the consequent impact on the environmental impact	Beverage	Abstract / Executive summary	EAFA website	Quantis	EAFA	2010	EU	yes, review not available	cork vs. screw tops	not listed
52	comparing packaging options	LCA	Life Cycle Assessment of food packaging made of Ingeo biopolymer and (r)PET	N/A	Report	NatureWorks website	IFEU	NatureWorks	2009	EU, US	no	PLA, rPET	NatureWorks, PlasticsEurope
53	comparing packaging options	LCA	Life Cycle Assessment of PolyLactide (PLA): A comparison of food packaging made from NatureWorks® PLA and alternative materials	N/A	Report	IFEU website	IFEU	NatureWorks	2006	DE	yes, review available	PET, PLA, PP, OPS	NatureWorks, other literature

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transparency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
AP, EP, GWP, ODP, SP, carcinogenic, ecotox, respiratory effects, resources	yes	lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	volume	unknown	N/A	cradle-to-gate	no	no	no
GWP	no	fully transparent	fully transparent	process-based LCA, attributional	standard 800 g loaf of sliced bread' made of wheat flour at industrial scale and consumed at home	other	other	cradle-to-table	yes, assumption	yes, sensitivity analysis	no
GHG emissions	no	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1 6-pack of Fat Tire amber ale	cut-off	100% to the product which uses the recyclate	cradle-to-table	no	no	yes
energy, waste, GHG emissions		lack of quantitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	varies based on study	unknown	unknown	cradle-to-grave	yes, assumption	yes, sensitivity analysis	no
energy, GHG	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	varies based on study	unknown	unknown	cradle-to-grave	yes, assumption	yes, sensitivity analysis	no
GHG emissions	no	lack of qualitative input transparency	fully transparent	process-based LCA, consequential	75 cL wine	unknown	unknown	cradle-to-grave	no	yes, sensitivity analysis	yes
CED, GWP, ODP, AP, EP	partially	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	to prepare one cup of coffee ready to drink at home the provision of one kg of butter ready to eat at home	cut-off	100% to the product which uses the recyclate	cradle-to-grave	yes, assumption	yes, sensitivity analysis	yes
AP, EP, GWP, ODP, SP, carcinogenic, ecotox, respiratory effects, water use, minerals	yes	fully transparent	lack of quantitative output transparency	process-based LCA, consequential	Processing and delivery of 1,000 kg pork chops	N/A	N/A	cradle-to-gate	yes, assumption	no	no
CED, GWP, ODP, AP, EP, POCP, costs, social	yes	fully transparent	fully transparent	process-based LCA, attributional	The distribution of 1.000 tons of fruit/vegetables either transported in wooden boxes, cardboard boxes (both one-way systems) or in plastic crates (multi way system).	avoided burden	100% to the product which generates recyclate	cradle-to-grave	no	yes, sensitivity analysis	no
Energy, GWP, ADP, SFP, AP, EP, water use, land use	yes	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1 m2 of packaging film	unknown	unknown	cradle-to-grave	no	yes, sensitivity analysis	no
GWP, PED, water, AP, POCP, EP, waste	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, consequential	750 mL bottle of wine	unknown	unknown	cradle-to-grave	yes, empirical data	unknown	no
Fossil, GWP, POCP, AP, EP, toxicity, land, PED	mostly	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	1 clamshell packaging	cut-off	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	no
Fossil, GWP, POCP, AP, EP, toxicity, land, PED	mostly	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	1 clamshell packaging	cut-off	100% to the product which generates recyclate	cradle-to-grave	no	yes, sensitivity analysis	no

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
54	comparing packaging options	LCA	Life cycle assessment for non-refillable PET systems, taking into account the secondary products	N/A	Report	IFEU website	IFEU	PETCORE	2004	DE	yes, review not available	PET, glass	other literature
55	comparing packaging options	LCA	Role of Packaging in LCA of Food Products	Food	Other	Towards Life Cycle Sustainability Management	F. Silvenius et al.		2011	FI	no	Laminate, plastic, corrugate	other literature
56	evaluating end of life options	LCA	Eco-efficiency of recovery scenarios of plastic packaging	Other	Report		TNO Environment, Energy and Process Innovation, P.G. Eggels et al.	APME	2001	BE	yes, review available	MSW: PE/PP films, PE/PP bottles and other rigid products, PET bottles and other rigid products, PS/EPS bottles and other rigid products, PVC films, PVC bottles and other rigid products. IW: PE/PP films, PE/PP crates and pallets, other PE/PP rigid products, and PS/EOS rigid products.	Fraunhofer Institut, BUWAL and CML, scientific research institutes in Germany, Switzerland and the Netherlands
57	evaluating end of life options	LCA	State 1 Report for Life Cycle Assessment of Packaging Waste Management in Victoria	Other	Report		Tim Grant, et al.	EcoRecycle Victoria	1999	AU	no	Glass bottles, PET soft drink bottles, steel cans	Direct collection of data, industry, literature
58	evaluating end of life options	LCA	Environmental Assessment of Municipal Waste Management Scenarios: Part I – Data collection and preliminary assessments for life cycle thinking pilot studies	Other	Report		K. Konecszy et al.	European Commission Joint Research Centre, Institute for Environment and Sustainability	2007	IT		MSW	Provided by governments of Bulgaria (Karlovo region), Cyprus, Czech Republic, Hungary (Kokeny region, city of Pecs), Lithuania (Riga), Malta, Poland (Krakow), Romania (Iasi region), and Slovakia (Topolcany).
59	evaluating end of life options	LCA	Bilan environnemental de filières de traitement de plastiques de différentes origines	N/A	Report		BIO Intelligence Service	ADEME	2006	FR	no	PE, PET, PLA, biodegradable polymers	
60	comparing packaging options	LCI	Cradle-to-Gate Life Cycle Inventory of Nine Plastics Resins and Four Polyurethane Precursors	N/A	Report		Franklin Associates	ACC, Plastics Division	2011	US	yes, review available	HDPE, LDPE, LLDPE, PP, PET, GPPS, HIPS, PVC, ABS, PU precursors	Franklin Assoc DB

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transparency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
Fossil, GWP, POCP, AP, EP, PED	yes	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	Packaging required to deliver 1,000 L beverage to consumer	other	other	cradle-to-grave	no	no	yes
AP, EP, GWP	partially	lack of qualitative input transparency	lack of quantitative output transparency	process-based LCA, attributional	1,000 kg of each product consumed	unknown	unknown	cradle-to-table	yes, empirical data	yes, sensitivity analysis	yes
ADP, Fuel resources depletion potential (EDP), GWP, ODP, HTP, AETP, POCP, AP, Nutrification Potential (NP), Final Waste (FW), Specific (hazardous) final waste (TW), Cumulative Energy Requirement (ENER)	N/A	fully transparent	fully transparent	process-based LCA, consequential	the "coherent treatment" of 1 kg "average" packaging plastics out of Municipal Solid Waste (MSW) and out of Industrial packaging Waste (IW)	avoided burden	unknown	cradle-to-grave	N/A	yes, sensitivity analysis	N/A
Greenhouse, Summer Smog, Acidification, Eutrophication, Solid Waste, Water Use	unknown	fully transparent	fully transparent	process-based LCA, consequential	The management of the recyclable fractions of glass containers, PET soft drink bottles and steel tin-plate packaging discarded at kerbside from the average Melbourne household in one week.	avoided burden	100% to the product which uses the recyclate	cradle-to-grave	N/A	yes, sensitivity analysis	N/A
Landfill Diversion, GWP, Air Emissions, Water Emissions	unknown	fully transparent	lack of quantitative output transparency	process-based LCA, consequential	The management of one tonne of municipal solid waste	avoided burden	unknown	cradle-to-grave	N/A	yes, sensitivity analysis	N/A
energy, waste, air & water emissions	partially	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1,000 lbs or 1,000 kg of resin	unknown	N/A	cradle-to-gate	no	no	no

ID	Focus	Method	Title	Food or beverage?	Reference Type	Source	Authors	Sponsors	Date	Location	Peer reviewed?	Packaging material	Background data
61	comparing packaging options	LCI	European Database for Corrugated Board Life Cycle Studies	N/A	Report	FEFCO website		FEFCO, Cepi Container Board	2009	EU	no	corrugate	primary (gate-to-gate)
62	comparing packaging options	LCI	LCI of Foam and Coated paperboard plates	N/A	Report	http://www.pactiv.com/About_Pactiv/LCI_Foam_PaperPlates_Final-Report.aspx	Franklin Associates	PACTIV	2009	US	yes, review available	PS foam, coated paperboard (LDPE or PS)	Franklin Assoc DB
63	comparing packaging options	LCI	LCI summary for eight coffee packaging systems	Beverage	Report		Franklin Associates	ACC, Plastics Division	2008	US	yes, review available	fiberboard, steel, plastic, laminate	Franklin Assoc DB, NREL US LCI DB, AA LCI
64	comparing packaging options	LCI	LCI summary for four half-gallon milk containers	Beverage	Report		Franklin Associates	ACC, Plastics Division	2008	US	yes, review available	glass, paperboard, HDPE, PLA	other literature
65	comparing packaging options	LCI	LCI summary for six tuna packaging systems	Food	Report		Franklin Associates	ACC, Plastics Division	2008	US	yes, review available	steel, plastic (PP, PET), Al foil, paper, paperboard	Franklin Assoc DB, NREL US LCI DB
66	comparing packaging options	LCI	Life Cycle Inventory of 16-ounce Disposable Hot Cups	Beverage	Report	http://www.microgreeninc.com/assets/files/White-Papers/LCI-02-2009-Bev-Cups.pdf	Franklin Associates	Microgreen Polymers	2009	US	yes, review available	RPET SMX, EPS foam, LDPE-paperboard, corrugate	Franklin Assoc DB, NREL US LCI DB, ecoinvent
67	comparing packaging options	LCI	Life Cycle Inventory of Foam Polystyrene, Paper-based, and PLA Foodservice Products	N/A	Report		Franklin Associates	Plastic Foodservice Packaging Group	2011	US	yes, review available	EPS, PLA, coated paperboard, GPPS	Franklin Assoc DB, NREL US LCI DB, other lit
68	comparing packaging options	LCI	Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products	N/A	Report		Franklin Associates	ACC, PS Packaging Council	2006	US	yes, review available	PS foam, coated paperboard, molded pulp	Franklin Assoc DB
69	comparing packaging options	LCI	Tinplate Life Cycle Inventory Study	N/A	Report		PE International	APEAL	2011	Western Europe	no	tinplate steel	GaBi

Impact categories	Complies w/ relevance matrix?	Input Transparency	Output Transpar-ency	Type	Functional unit	Allocation	Credits recycling	System boundaries	food losses considered?	Includes uncertainty assessment	secondary / tertiary packaging included?
N/A	N/A	fully transparent	fully transparent	process-based LCA, attributional	1 ton product	avoided burden	100% to the product which uses the recyclate	gate-to-gate	no	no	no
energy, waste, GHG emissions	partially	fully transparent	fully transparent	process-based LCA, attributional	The present study compares a 4.68 gram foam plate with a 12.1 gram coated paper plate. (plates of similar strength)	avoided burden	50%/50% to both products	cradle-to-grave	no	no	yes
energy, waste, air & water emissions	partially	fully transparent	fully transparent	process-based LCA, attributional	100,000 ounces of ground coffee	avoided burden	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	no
energy, waste, air & water emissions	partially	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	10,000 containers, as all containers contain equivalent milk amounts	cut-off	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	no
energy, waste, air & water emissions	partially	fully transparent	fully transparent	process-based LCA, attributional	100,000 ounces of tuna consumed	avoided burden	50%/50% to both products	cradle-to-grave	no	yes, sensitivity analysis	no
energy, waste, GHG emissions	partially	fully transparent	fully transparent	process-based LCA, attributional	production and end-of-life management of 10,000 single-use 16-ounce hot cups and associated packaging	avoided burden	100% to the product which uses the recyclate	cradle-to-grave	no	yes, sensitivity analysis	yes
energy, waste, GHG, water	partially	fully transparent	fully transparent	process-based LCA, attributional	10,000 items of each foodservice product	avoided burden	N/A	cradle-to-grave	no	yes, sensitivity analysis	no
energy, waste, air & water emissions	partially	lack of qualitative input transparency	fully transparent	process-based LCA, attributional	10,000 foodservice product units	avoided burden	50%/50% to both products	cradle-to-grave	no	no	yes
GWP, AP, EP, POCP, PED	partially	lack of quantitative input transparency	fully transparent	process-based LCA, attributional	1 kg tinplate steel	avoided burden	100% to the product which generates recyclate	cradle-to-gate	N/A	no	N/A

Table D2: Attribute matrix of LCA studies reviewed—research questions and preliminary learnings

ID	Title	What is the value & relevance of a life cycle approach?	What is the value & relevance of including all life cycle stages?	What is the value & relevance of including multiple LCI flows and impact categories?	What is the value & relevance of including the food and/or beverage?
1	Case Studies Life Cycle Assessment of a Basic Lager Beer		Illustrate which stage drives impact	Different product systems preferred based on impact category choice	Clear that beer is a significant contributor to impact, but less clear if beer or the packaging is driving transportation impact
2	Coffee: family and portion pack showing the relative importance on environmental impact of different consumer habits relating to coffee preparation and consumption.		Show packaging contributes only small fraction to overall system impact		Coffee, milk, hot water preparation dominate impact
3	Comparative LCA of 4 types of drinking cups used at events		Different LC stages dominate based on impact category	Different product systems preferred based on impact category choice	N/A
4	Comparative Life Cycle Assessment of beverage cartons cb3 and cb3 EcoPlus for UHT milk		Illustrate which stage drives impact	Different product systems preferred based on impact category choice	N/A
5	Comparative Life Cycle Assessment of Malt-based Beer and 100 per cent Barley Beer				
6	Analysis of the life cycle of Tetra Pak packaging			N/A (Different impact categories don't provide much new information)	N/A
7	Environmental effects from a recycling rate increase of cardboard of aseptic packaging system for milk using life cycle approach	Use LC approach (rather than intuition) to illustrate that recycling is preferred	N/A (not broken down by LC stage)	Show which emissions / consumed resources are driving impact	N/A
8	Environmental impact of packaging and food losses in a life cycle perspective			N/A	Shows that increasing impact of packaging may be beneficial if it reduces amount of food waste
9	Environmental impacts of conventional plastic and bio-based carrier bags: Part 1 - Life cycle production		Under certain conditions, bio-based bags are not "better" than PP bags		N/A
10	Environmental impacts of conventional plastic and bio-based carrier bags: Part 2 - EoL		EoL impacts less significant than production stage impacts		N/A
11	Environmental impacts of packaging and packaged food - Role of packaging		Illustrate which stage drives impact -- food loss can be on same order as packaging	Changing impact category doesn't appear to alter conclusions	Product processing dominates impact, followed by packaging and losses
12	Environmental implications and market analysis of soft drink packaging systems in Mexico. A waste management approach				N/A
13	Environmental Life Cycle Assessment (LCA) Case Studies for Western Australian Grain Products				
14	Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking & Assessment: A Sustainable Materials Management Demonstration Project		Show that transportation dominates and storage / retail is a minor fraction of overall impact		Can alter material preference
15	Investigating the life-cycle environmental profile of liquid food packaging systems	Understand which phases drive impacts and why; use to address potential system losses	Illustrate which stage drives impact -- in this case, raw materials and apple juice / milk		Beverage production may or may not dominate environmental burden
16	LCA of a Roast Stored in Aluminium Household Foil		Show that food distribution and preparation matter as well as food production; packaging represents minor contribution to impact	Distribution LC stage is important for some flows, but not for others	Food production and distribution drive impact; packaging is of secondary importance
17	LCA of an Italian lager beer		N/A (not broken down)		N/A (unclear from results)
18	LCA of Chocolate Packed in Aluminium Foil Based Packaging		Show packaging contributes only small fraction to overall system impact		Chocolate and milk production dominate impact
19	LCA of Packed Food Products - the function of flexible packaging - Case Study: Butter		Show packaging contributes only small fraction to overall system impact	N/A (Doesn't vary much between categories)	Butter production drives impact in all categories considered
20	LCA of packed food products: Deep-frozen spinach		Show packaging contributes only small fraction to overall system impact	Different LC stages drive impact for different impact categories	Spinach production drives eutrophication

What are characteristics of future LCAs that should be considered?	How do LCA results connect or contradict the waste management hierarchy?	Preliminary learnings
	N/A	Beer transport is a key impact driver (POCP, AP); alternative logistics could potentially reduce impact
		Food preparation matters -- in particular heating water Coffee production, milk production, and brewing dominate impacts; transportation and packaging are only minor components regardless of metric
	Reusable cup (PC) isn't always associ-ated with lowest impact	Results show that reusable cup isn't always associated with the lowest impact for a given impact category. Additionally, preference for reusable vs. disposable cups will depend on event scale.
		New product is preferred for most impact categories
	N/A	Doesn't include packaging -- food only LCA
	Aseptic packaging has lower impact despite lower recycling rates	Use of aseptic packaging can reduce impact (even though it has lower recycling rates) compared to glass or plastic packaging Advantage from renewability of cardboard, as well as its lower mass
	Higher recycling rate leads to reduction in energy use and natural resource use	Consistent with hierarchy: recycling cardboard leads to lower energy and resource consumption (although to higher TDS emissions) Results are specific to Brazilian situation; may not be applied universally
	N/A	May be necessary to increase impact associated with packaging in order to reduce impact due to food waste -- and thereby overall system impact Especially true for foods with high losses or high impact relative to packaging
		Preferred bag material depends on energy sources: Clean energy is necessary for bio-based bags made in the US and shipped to Singapore to appear more favorable than locally produced PP bags
	Minimize impact by composting bio-bags; landfill leads to highest impact	Composting bio-material bag generates the lowest impact Preference for bio-bag will depend on EoL scenario as well as energy sources from production
	N/A	Buying in bulk may not be environmentally friendly if food is wasted Food production dominates environmental impact with impact due to losses on same order as impact due to packaging Need smart packaging design -- minimize packaging materials subject to package's ability to fulfill other functions A package's environmental impact will depend on its material AND design
	At some point, burden to collect and recycle PET outweigh benefit of avoided production from recycling	Higher PET recycling rate not necessarily better--at some point, resources needed to collect the marginal bottle outweigh benefit of recycling that bottle Material production represents highest impact; therefore, should recycle material in order to avoid production of primary
	N/A	Bread: dominated by farming, retail & consumption; transportation is minor Beer: Dominated by farming (ecotox, EP) and by storage & processing Cooking oil: dominated by farming (ecotox, EP) and by retail Transportation is consistently a minor contributor to LC impact; Farming is consistently a key driver of EP and ecotox due to pesticides, fertilizer
Account for food losses		Transport (may require climate-control), tomato growth, and packaging play a large role in environmental impact Assuming no food loss, PET has the highest burden and loose tomatoes have the lowest; when food loss is taken into account, PS is preferred
		Apple juice: Impact driven by raw materials and food production; filling and package distribution are minor; food accounts for ~50% impact when included and contributes significantly to distribution impact Milk: Food production dominates impact when included; without it, raw materials dominate plus filling losses
		Since roast production (and distribution/selling) drive impact, one shouldn't throw away leftover roast -- instead, store it in aluminum foil If product is refrigerated, distribution can have a significant impact
		Comparison of two beer packaging systems…but results presented as normalized & weighted
		Chocolate dominates overall impact; distribution, transportation to household, and packaging are only minor contributors Choice of chocolate type (white vs. milk vs. dark) has the largest influence on impact
		Butter production -- specifically, provision of milk -- dominates the overall impact; longer storage of butter in fridge has minimal impact on burden Increasing spoilage rate to 33% increases impacts about 49%
		Food production, distribution, and storage drive system impact (the latter two due to climate control requirements) Packaging and preparation are only minor contributors

ID	Title	What is the value & relevance of a life cycle approach?	What is the value & relevance of including all life cycle stages?	What is the value & relevance of including multiple LCI flows and impact categories?	What is the value & relevance of including the food and/or beverage?
21	LCA of Ready-to-Serve Goulash Soup Packed in Stand-Up Pouches		Show packaging contributes only small fraction to overall system impact		
22	LCA of Ready-to-Serve Lasagne Bolognese Packed in Aluminium Foil Containers		Show that food distribution and preparation matter as well as food production; packaging represents minor contribution to impact	Different LC stages dominate according to selected impact category	All stages except packaging dominate impact
23	LCA of Yoghurt Packed in Polystyrene Cup and Aluminium-Based Lidding	x	Show that food distribution and preparation matter as well as food production; packaging represents minor contribution to impact	Distribution LC stage is important for some flows, but not for others	Yogurt production (milk) is a key contributor to impact
24	Life cycle analysis of bread production – a comparison of eight different options				N/A (Only covers bread production)
25	Life cycle assessment of bread produced on different scales		Illustrate which stage drives impact		Food production and distribution drive impact; packaging is of secondary importance
26	Life cycle assessment of consumer packaging for liquid food		Illustrate which stage drives impact -- in this case, typically raw materials	Tetra Pak favorable for GWP, but on par with plastic for EP	N/A
27	Life cycle assessment of different reuse percentages for glass beer bottles		N/A	Alternative impact categories do not affect preferred material	N/A
28	Life cycle assessment of drinking Darjeeling tea	x	Illustrate which stage drives impact -- in this case, tea preparation and cultivation		Beverage production and user behavior drive impact; packaging accounts for only minor fraction
29	Life Cycle Assessment of Drinking Water Systems: Bottle Water, Tap Water, and Home/Office Delivery Water		Show relative impact among LC stages, esp. for different materials	Key drivers can differ between impact categories (focus on bottled water)	Beverage impact doesn't matter
30	Life Cycle assessment of frozen cod fillets including fishery-specific environmental impacts				Packaging accounts for only a small fraction of overall impact
31	Life cycle assessment of polylactic acid and polyethylene terephthalate bottles for drinking water		Adding EoL can alter preference	Changing impact category can alter preference	N/A
32	Life Cycle Assessment of Supermarket Carrier bags		Show that raw materials and bag production dominate; transportation is a minor contributor		N/A
33	Life Cycle Assessment of the Stonyfield Farm Product Delivery System	Apply to different packaging designs - doesn't always follow a trend due to changes in design	Illustrate which stage drives impact -- in this case, material production and distribution (with yogurt)		N/A
34	Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots		N/A	A couple scenarios illustrate changing impact category can affect material preference	N/A
35	Life Cycle Assessment of Yogurt Cups made from PS and Ingeo PLA based on Existing Literature and Current Inventory Data				N/A
36	Product Category Rules (PCR) for preparing an Environmental Product Declaration (EPD) for Product Group: Wild caught fish				
37	Resource and Environmental Profile Analysis of Polyethylene and Unbleached Paper Grocery Sacks		N/A		N/A
38	Resource and Environmental Profile Analysis of Polyethylene Milk Bottles and Polyethylene-coated Paperboard Milk Cartons				N/A
39	Single Use Cups or Reusable (coffee) Drinking Systems: An Environmental Comparison		N/A	Scenarios illustrate that changing impact category can affect material preference	N/A
40	Subjective Choices in Life Cycle Assessment: How many alternatives are enough?				N/A

What are characteristics of future LCAs that should be considered?	How do LCA results connect or contradict the waste management hierarchy?	Preliminary learnings
		Goulash production drives impact despite consisting of 58.9% water by mass Packaging and transport from supermarket to household are of secondary importance Important packaging issues are the lamination process and the production of raw materials
		Lasagna production and [refrigerated] distribution/selling dominate impact; food preparation and storage also important for certain impact categories Packaging and transport from supermarket to household are of minor importance
		Production of yogurt accounts for majority of impact for most indicators due to provision of milk; distribution and selling are also important due to refrigeration; packaging accounts for 2-20% of impact
	N/A	Organic farming of grains can reduce impact Baking bread at home has higher footprint than at a factory or bakery
	N/A	Packaging is typically a small component of bread LC impact; agriculture, food processing, and transportation typically dominate
	N/A Not enough details	Tetra Pak has lower GWP than PET or HDPE bottles but potentially higher EP; for the bottles, impact driven by raw materials and waste management Use of aseptic package doesn't necessarily reduce footprint (minimal change in transport impact, but need metals, plastic to compensate) Ideally minimize materials use; use renewable materials and 'green electricity"
	Reusing bottles decreases impacts in all categories considered	Returnable bottles have lower footprint over lifetime; however, this will ultimately depend on number of times bottle is reused because bottle has higher up-front impact
	N/A	Tea cultivation and preparation (boil water) drive GWP and CED due to electricity usage Coffee has higher cultivation impact than tea
		Packaging is important in the bottled water life cycle Energy consumption driven by production of bottles, lids, and secondary packaging, as well as long-haul transport No impact associated with water other than its consumption; however, includes impact of processing the water
	N/A	Impact driven by fishery; packaging accounts for only a small fraction of impact Provides suggestions how to reduce fishery impact
		Cradle-to-gate: PLA bottles use lower energy and have lower GWP, but higher AP and EP compared to PET bottles PLA impact due to pesticides - shows up on Human Health and Ecosystem Quality (EciIndicator 99) However, PLA can be favorable assuming it can be recycled (which systems are currently not set up to do)
	Reuse bag several times to reduce impact; may need to reuse 100+ times for impact to be comparable to conventional HDPE bag	Impact dominated by resource use and production; transport, secondary packaging, and EoL have minimal contribution Polypropylene bag has highest impact due to raw material production; cotton impact primarily due to raw materials production Bio-degradable bag has higher impacts in some categories due to greater weight and higher production impacts
	Larger containers enable reduction in solid waste for transport of same amount of product	Raw materials and (refrigerated) distribution account for most of energy burden Larger containers lead to lower burdens (not counting consumer product waste) Smaller containers also have lower energy burdens due to change in packaging configuration Use of paperboard can reduce energy consumption, but increases solid waste (measured by kg)
	less recycled material (i.e. PP) preferred over more recycled material	Results show polypropylene as the preferred material due to its lower production and EoL impacts, lighter mass, alternative preservation technology PP has lower overall impact than glass despite the former's lower recycling rate Logistics are also important
	N/A	Polymer production drives impact PLA AP driven by corn production and corn-to-PLA conversion
	N/A	Doesn't include packaging Represents prescription for LCA -- not LCA results
	Atmospheric emissions increase with paper sack recycling rate	PE sacks require less energy assuming a zero recycling rate; as recycling rate increases, paper sack becomes more favorable PE sacks are associated with lower waste and lower emissions than paper sacks regardless of recycling rate May be able to change consumer behavior to reduce bag usage patterns (and impact)
	Reduce waste by selling food in "bulk"	Larger HDPE container preferred over smaller HDPE container and LDPE-coated paperboard container Reduce waste by selling food in larger containers
	Disposable cups have lower environmental burdens	User behavior greatly influences environmental burden of reusable cup & saucer and earthenware mug Disposable cups shown to have lower environmental burdens; however, study doesn't consider waste generated by disposable systems Includes cost and shadow price assessment
Need to understand qualitative choices that can lead to different conclusions. Can potentially address w/ sensitivity analysis	N/A	Choices regarding LCA data, methodology, etc. can alter a study's conclusion An LCA practitioner needs to be aware of this

ID	Title	What is the value & relevance of a life cycle approach?	What is the value & relevance of including all life cycle stages?	What is the value & relevance of including multiple LCI flows and impact categories?	What is the value & relevance of including the food and/or beverage?
41	Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers		N/A		N/A
42	The carbon footprint of bread		Illustrate which stage drives impact (wheat cultivation, consumption, bread production)	Choice of packaging has minimal impact on results	Packaging accounts for only a small fraction of overall impact
43	The Carbon Footprint of Fat Tire Amber Ale		Illustrate which stage drives impact	N/A (GHG emissions only)	Packaging accounts for a larger impact due to the weight of glass
44	The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe		Need to include functional unit in order to compare packaging designs	N/A	Addresses food losses
45	The impact of plastics on life cycle energy consumption and GHG emissions in Europe				
46	The life cycle emissions of wine imported to the UK		Illustrate which stage drives impact	N/A	N/A
47	The role of flexible packaging in the life cycle of coffee and butter		Find key impact drivers…could even be food preparation (rather than the food)		Food / beverage production drives impact; packaging of secondary importance
48	The sustainability of communicative packaging concepts in the food supply chain. A case study: part 1. Life cycle assessment		N/A (Doesn't breakdown output into different LC stages)	N/A (Different impact categories don't provide much new information)	Need to include food to show benefits of new packaging design
49	The Sustainability of Packaging Systems for Fruit and Vegetable Transport in Europe based on Life-Cycle-Analysis – Update 2009			A couple scenarios illustrate changing impact category can affect material preference	N/A
50	Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings		Transport accounts for only a minor fraction of impact	N/A (Different impact categories don't provide much new information)	N/A
51	Wine: effect of different closure systems on wine loss due to tainting and the consequent impact on the environmental impact		N/A	N/A	Address failure of cork stoppers in wine -- leads to greater loss than screw top
52	Life Cycle Assessment of food packaging made of Ingeo biopolymer and (r)PET				N/A
53	Life Cycle Assessment of PolyLactide (PLA): A comparison of food packaging made from NatureWorks® PLA and alternative materials		Illustrate which stage drives impact -- in this case, typically raw materials	Certain LC stages account for a larger fraction of impact in different impact categories	N/A
54	Life cycle assessment for non-refillable PET systems, taking into account the secondary products				N/A
55	Role of Packaging in LCA of Food Products				
56	Eco-efficiency of recovery scenarios of plastic packaging				
57	State 1 Report for Life Cycle Assessment of Packaging Waste Management in Victoria				
58	Environmental Assessment of Municipal Waste Management Scenarios: Part I – Data collection and preliminary assessments for life cycle thinking pilot studies				
59	Bilan environnemental de filières de traitement de plastiques de différentes origines				
60	Cradle-to-Gate Life Cycle Inventory of Nine Plastics Resins and Four Polyurethane Precursors				N/A
61	European Database for Corrugated Board Life Cycle Studies		N/A	N/A	N/A
62	LCI of Foam and Coated paperboard plates		Illustrate which stage drives impact; compare different materials with different hot spots		N/A
63	LCI summary for eight coffee packaging systems	Use LC approach (rather than intuition) to show that flexible packaging is preferred			N/A
64	LCI summary for four half-gallon milk containers		N/A (not broken down)	Different product systems preferred based on impact category choice	N/A
65	LCI summary for six tuna packaging systems				N/A

What are characteristics of future LCAs that should be considered?	How do LCA results connect or contradict the waste management hierarchy?	Preliminary learnings
	N/A	Results indicate trade-off between LCA impact and green design principles for bio-polymers Need to acknowledge value choices and subjectivity of green design principles and LCIA weighting
	N/A	Wheat cultivation and consumption drive bread impact; depends on consumer behavior (e.g. toasting, refrigerating) Consequently, specific type of bread or packaging has minimal effect on overall impact
	N/A	Retail (refrigeration), glass production, and barley production are key impact drivers, along with distribution
	Plastic packaging reduces overall GHG emissions, even without recycling	Packaging = 1.7% of EU consumer carbon footprint; Includes comparison per kg and per functional unit Study goal is to prove that plastic packaging increases food shelf life, thereby lowering overall carbon footprint
		Substitution by plastics enable Europe to hypothetically reduce energy demand and GHGs Under current waste management conditions, conventional plastics are preferred to bioplastics
		Focus is primarily on transportation of wine from Australia / France to UK Contains data that shows that packaging can account for 17.4% of impact
		Coffee: brewing and coffee production are important, the study highlights consumer behaviour and packaging related measures to reduce impacts. Butter: milk is dominating results. Packaging has low impacts. Storage time in freezer (consumer behaviour) is relevant.
		Illustrates how alternative food packaging design can improve food shelf life and thus reduce losses In this case, new design adds minimal mass to original package…but impact of this is not quantified
		Wood box: impact driven by both production and service life Cardboard box: impact driven by production Plastic box: impact driven by service life (reusable)
	Maybe use to compare with another study to understand benefits of flexible packaging?	Tries to understand whether bio-based materials are suitable for packaging in the first place Bio-based polymers offer opportunities for impact reduction; however, depends on variations in land use impact Still gaining experience in bio-material production and processing -- expect Outer packs will be better because less demanding barrier properties
Address whole product system		Create a more representative comparison of stoppers by addressing wine loss, specifically due to "corked taste" New stopper is preferable despite its higher materials GWP due to beverage loss reduction
		Plastic production dominates
		Plastic production dominates
		PET: materials and production dominate Glass: transport has a larger impact than in PET
		Study purpose is to create plastic resin LCIs
	N/A	Goal is to create a gate-to-gate LCI of corrugate; doesn't include impact assessment
		Mass drives impact results: with the exception of solid waste by volume, PS foam has consistently lower flow quantity totals than paperboard plates
	Brick pack and laminate bag are associated with the lowest energy use despite no recycling	Steel can energy use driven by steel production Plastic canisters associated with higher energy consumption than steel cans (require energy fuel resources) despite higher EoL energy credit Steel can has highest solid waste by weight, but plastic is comparable when solid waste is measured by volume; laminate bag & brick pack are lowest
	Refillable glass bottle corresponds with lowest LC energy use, but higher GHG, waste	Glass is preferred based on energy, but has higher waste (heaviest container) and GHG impact despite being reused 8 times PLA requires the most energy for production, even if energy of corn were not included
	12-oz pouch is associated with the lowest energy use despite no recycling	The flexible pouch is associated with the lowest energy use and GHG emissions (despite no recycling)

ID	Title	What is the value & relevance of a life cycle approach?	What is the value & relevance of including all life cycle stages?	What is the value & relevance of including multiple LCI flows and impact categories?	What is the value & relevance of including the food and/or beverage?
66	Life Cycle Inventory of 16-ounce Disposable Hot Cups			REPT SMX requires the least amount of energy, but is not associated with the least amount of solid waste by mass	N/A
67	Life Cycle Inventory of Foam Polystyrene, Paper-based, and PLA Foodservice Products		Illustrate which stage drives impact	Different packaging options are associated with lower impact for different LCI flows	N/A
68	Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products				N/A
69	Tinplate Life Cycle Inventory Study		N/A		N/A

	What are characteristics of future LCAs that should be considered?	How do LCA results connect or contradict the waste management hierarchy?	Preliminary learnings
			When working with recycled content, allocation approach choice (cut-off vs. 50/50) can affect material favorability Insulated sleeve increases paper cup's impact
		Only landfill and incineration considered	Foam products are lighter weight than paperboard and PLA -- leads to lower solid waste by mass (but not by volume) Energy requirements for PS and LDPE-coated products are similar, but generally lower than PLA and paperboard products PLA system has significant process GHG emissions from fertilizer use
			Plastic products are generally associated with lower solid waste by weight Preferred material depends on product type (cups vs. plates vs. clamshells) and on inventory flow (energy vs. solid waste vs. GHG)
	Understand technology evolution, even for well-understood processes	N/A	Illustrates changes in environmental performance between previous update in 2006 and current 2008 data

Appendix E: International Life Cycle Board & Technical Review Committee Panel

Review of the Final Report

"Analysis of life cycle assessment in packaging for food & beverage applications"

Reinout Heijungs, CML, Leiden University, 25 February 2013

Dear members of the LC Initiative,
I am impressed by the constructive and rapid response that your team of authors has been able to give. I think you dealt with many critical and sometimes conflicting comments in a very good way. All changes have been accepted.

Kind regards,
Reinout

Review report of the draft

"Analysis of life cycle assessment in packaging for food & beverage applications"

UNEP/SETAC Life Cycle Initiative, 2012

Reinout Heijungs, CML, Leiden University, 11 January 2013

Introduction

Within the UNEP/SETAC Life Cycle Initiative, a group led by Bruce Vigon has been conducting a project on knowledge mining of LCAs, with a focus on Food and Beverage Packaging. A draft report with the title "Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications" has been written.

A Type 2 Peer Review Process has been set-up. On 12 December 2012, Sonia Valdivia invited four persons with a nice balance in terms of continent, gender, and affiliation, to perform a review. The text of the email used for the invitation is reproduced in Appendix A.

One person declined to do the review for reasons of unavailability, and another person was asked as substitute. Between 31 December 2012, and 7 January 2013, the four reviews were received. In addition, two reviews from the side of UNEP were received.

This report provides a synthesis of the main points brought up by the six reviewers. It has been made by the Chair of the Technical Review Committee of the UNEP/SETAC Life Cycle Initiative, by and large on the basis of the reviewer statements, but here and there nuanced by his own judgment.

Relevance

Overall, the reviewers acknowledge the importance of the report, and endorse the use of knowledge mining as an approach in generalizing from individual studies.

Readability and structure

There are several issues concerning the set-up of the report. The executive summary condenses what has been done, but not what came out.

Approach taken

Although the idea of knowledge mining is widely supported, the details of the methodology is unclear to most reviewers. In particular, the relation between the attribute matrix (Table 3) and the results is unclear, and some of the conclusions do not follow logically from the text. Further, the added value of the method on top of a normal "common sense" approach is not always clear.

Suitability for the target group

Some reviewers are concerned that the technical nature of the report will distract the readers from the message that is supposed to be conveyed.

Detailed comments

The reviewers pointed out numerous bigger and smaller issues, from wording to references, from structure to methodology.

Conclusions

There are a couple of issues, some of which require conflicting solutions. I think that the report, which definitely deserves attention, would be improved by adding a long appendix on the technique used. Some of the present technical details could be shifted to that appendix, and other details should be added. Further, the executive summary should be improved.

Email Request for Feedback

As you may be aware a UNEP/SETAC Life Cycle Initiative project group led by Bruce Vigon has been conducting a project on knowledge mining of LCAs for about the past year. The focus area was Food and Beverage Packaging. That project has progressed to the point where a draft report has been prepared on: "Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications"

The project is designed to do four things:

1. assess identified and suitable LCAs that have been published in the subject area (methodology for determining key attributes and relevancy is described in the report) against their ability collectively and individually to answer a suite of research questions, leading to overall learnings about the strengths of LCA, its limitations or the congruency or lack thereof with other perspectives and rules of thumb (as for example the waste management hierarchy),
2. create general guidance to assist practitioners in the future to conduct knowledge mining of LCAs (consistent with the results of the UNEP/SETAC LC Initiative Knowledge Mining Workshop conducted in October 2011),
3. create general guidance for policy makers, packaging designers, and LCA practitioners for incorporating life cycle considerations in their work, and
4. develop recommendations on improving the conduct of LCAs for food and beverage packaging based on the learnings generated by this study.

The target audience policy makers, packaging designers, and LCA practitioners.

To assure a high level of quality and the international recognition of the work and as per the procedures of a UNEP/SETAC Life Cycle Initiative Type 2 Peer Review Process for publications, we are setting-up a Stakeholder process and a Review Committee (RC) and we would be very pleased to be able to count on you as a member of the RC.

If you kindly accept the invitation, please take into account the following questions for the review and use the template attached to facilitate your review:

1. Do you find that the definition of knowledge mining proposed in the report is applicable for other product chains and towards assisting policy makers, packaging designers, and LCA practitioners for incorporating life cycle considerations in their work?
2. Does the methodology developed and applied support the learnings extracted from the nearly 70 LCAs judged to be applicable to address these questions in a defensible and credible manner?
3. One element of the methodology intended to increase the technical credibility of the methodology is a set of matrices used to judge the attributes of the information base and the relevancy of studies. Could you comment on the ability of this approach (matrices developed) to demonstrate what aspects are essential and whether the explanation on this part of the methodology is clear and unambiguous?

To acknowledge the contribution of the RC members, the names of the members will be published in the acknowledgement section of the publication. Moreover, UNEP, through the Leiden University, could compensate your professional contribution to the review process with USD 400. The deadline for reviews is 30 December.

Following our planning, the publication is scheduled to be launched in 2013 in conjunction with an international conference.

The document has effectively less than 50 pages including pictures and tables.

The co-chair of the Review Committee is Reinout Heijungs (CML, University of Leiden) who will be kindly following up the review process. Please confirm at your earliest convenience, but no later than Friday 14th Dec, if you would be able and willing to join the Review Committee. If you would need an extension of few more days after the 30th of Dec. to deliver your review statements, please let me know by when the review could be done. We hope to hear from you soon and please let us know if you have any questions.

Review

Part A: General comments

The study "Analysis of LCA in Packaging & Beverage Applications" shows the importance of consolidating knowledge from previous experience gained in LCA studies in order to guide future packaging LCAs, packaging design and decision-making. The study aims to be of general application to others sectors too.

In general the structure of the study is quite good, Section 7 provides good general recommendations for LCA practitioners and Sections 5 and 7 are good and practical and focus to the different target audiences.

It is recommended to work more thoroughly in the contents of sections 3 and 8; it is advisable to include annexes with the complete attribute matrices.

1. Do you find that the definition of knowledge mining proposed in the report is applicable for other product chains and towards assisting policy makers, packaging designers, and LCA practitioners for incorporating life cycle considerations in their work?

    a. The use of knowledge mining as proposed in this study is indeed valuable to assist those involved in the implementation and use of a food and beverage packaging LCA. The study does not provide a "new" or "different" definition of knowledge mining, rather a specific application for LCA. Therefore it is strongly suggested that together with the "general" definition given more information about its development in IT and other fields is provided. It is mentioned that the framework can be used for other value chains, but it is not clear which aspects are of general application and which should be reviewed and adapted for a specific context.

2. Does the methodology developed and applied support the learnings extracted from the nearly 70 LCAs judged to be applicable to address these questions in a defensible and credible manner?

    b. It was not possible to evaluate the attribute matrix (Figure 3) and its relationship with the results of the study. It is also not clear how the attributes and research questions were selected. It is mentioned that an interactive process was used to select attributes and review the research questions, but more detail should be given in order to understand and for future applications. The list of knowledge mining reference includes only 59 not 70.

3. One element of the methodology intended to increase the technical credibility of the methodology is a set of matrices used to judge the attributes of the information base and the relevancy of studies. Could you comment on the ability of this approach (matrices developed) to demonstrate what aspects are essential and whether the explanation on this part of the methodology is clear and unambiguous? The concept of the relevance matrix to ensure the quality of the studies selected is quite good, but the methodology is not clear. It is especially important to understand the role of the reviewer "with extensive knowledge in LCA" and his role in the selection of studies, and definition of attributes and attribute value".

Part B: Detailed Comments are not produced here but are available on request


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About SETAC

The Society of Environmental Toxicology and Chemistry (SETAC) is a professional society in the form of a non-forprofit association, established to promote the use of a multidisciplinary approach to solving problems of the impact of chemicals and technology on the environment. Environmental problems often require a combination of expertise from chemistry, toxicology, and a range of other disciplines to develop effective solutions. SETAC provides a neutral meeting ground for scientists working in universities, governments, and industry who meet, as private persons not bound to defend positions, but simply to use the best science available.

Among other things, SETAC has taken a leading role in the development of Life Cycle Management (LCM) and Life Cycle Assessment (LCA).

The organization is often quoted as a reference on LCA matters.

For more information,see

www.setac.org

About the UNEP Division of Technology, Industry and Economics

Set up in 1975, three years after UNEP was created, the Division of Technology, Economics (DTIE) provides solutions to policy-makers and helps change the business environment by offering platforms for dialogue and co-operation, innovative policy options, pilot projects and creative market mechanisms.

DTIE plays a leading role in three of the six UNEP strategic priorities: climate change, harmful substances and hazardous waste, resource efficiency.

DTIE is also actively contributing to the Green Economy Initiative launched by UNEP in 2008. This aims to shift national and world economies on to a new path, in which jobs and output growth are driven by increased investment in green sectors, and by a switch of consumers' preferences towards environmentally friendly goods and services.

Moreover, DTIE is responsible for fulfilling UNEP's mandate as an implementing agency for the Montreal Protocol Multilateral Fund and plays an executing role for a number of UNEP projects financed by the Global Environment Facility.

The Office of the Director, located in Paris, coordinates activities through:

> **The International Environmental Technology Centre** - IETC (Osaka), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.

> **Sustainable Consumption and Production** (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.

> **Chemicals** (Geneva), which catalyzes global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.

> **Energy** (Paris and Nairobi), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.

> **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.

> **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies. This branch is also charged with producing green economy reports.

UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.

For more information,see

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Packaging plays a critical role in the labeling, transportation, protection, and preservation of food and beverage products. Growing concern for the environment, combined with the ubiquity and visibility of packaging, however, has led to increasing scrutiny of packaging's environmental burdens by a variety of stakeholders.

This report summarizes the results of a project designed to consolidate outcomes of existing research on the environmental performance of packaging, namely life cycle assessment (LCA) studies, in order to demonstrate the value of applying LCA to inform decisions when evaluating food and beverage packaging.

To achieve the goals of this study, the authors systematically analyzed 69 existing LCA studies to extract key points and identify knowledge and learnings that illustrate the value of LCA. The studies evaluated demonstrated the value of taking a life cycle approach to answer the questions posed by the various researchers of the analyzed studies. Additionally, illustrating the value of applying LCA to food and beverage packaging, the learnings are also drawn upon to provide practical advice for conducting future food and beverage packaging LCAs.

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